

RHIC II Physics Overview



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Brookhaven National Laboratory, Upton, NY

Outline of the Talk

What are the **new physics questions** that can be addressed with **detector and luminosity upgrades** at RHIC?

Spin physics with RHIC upgrades / RHIC II

- Example of transverse spin observables

The A+A program with RHIC upgrades / RHIC II

- Precision physics with high- p_T jets, high- p_T particle correlations
- Direct measurements of open heavy flavor
- Direct photon physics, photon-hadron correlations

The d+A program with RHIC upgrades / RHIC II

- Possibility for gluon saturation physics at forward rapidity, eRHIC case
- Longitudinal dynamics, energy loss, dynamical shadowing

Other compelling questions to benefit from RHIC upgrades / RHIC II

- Thermalization of the QGP, viscosity, elliptic flow, quarkonia, dileptons ...

Drell-Yan Physics with Possible New Detector

Transversity : **correlation** between transverse proton spin and quark spin **M. Grosse-Perdekamp, (2006)**

$$A_{TT} \propto \delta q(x_1) \delta q(x_2)$$

Sivers : **correlation** between transverse proton spin and quark transverse momentum

$$A_T \propto q(x_1) \cdot \bar{f}_{1T}^{\perp q}(x_2, k_\perp^2) \cdot \frac{(\hat{P} \times \vec{k}_T) \cdot \vec{S}_P}{M}$$

Boer/Mulders: **correlation** between transverse quark spin and quark transverse momentum

$$N(\phi) \propto h_1^{\perp q}(x_1, k_\perp^2) \cdot \frac{(\hat{P} \times \vec{k}_\perp) \cdot \vec{S}_q}{M} \cdot h_1^{\perp \bar{q}}(x_2, \bar{k}_\perp^2) \cdot \frac{(\hat{P} \times \vec{\bar{k}}_\perp) \cdot \vec{S}_{\bar{q}}}{M}$$

Process Dependence in QCD

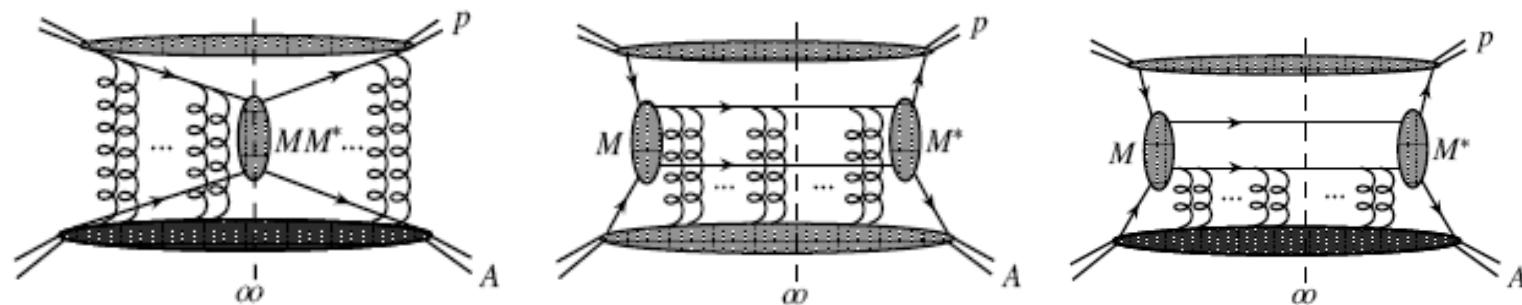
- The generalized (lack of) universality of the Sivers function (effect)

Brodsky, Huan, Schmidt, (2002),

SDID to DY change sign

...

- Analogy to unpolarized coherent scattering in nuclei



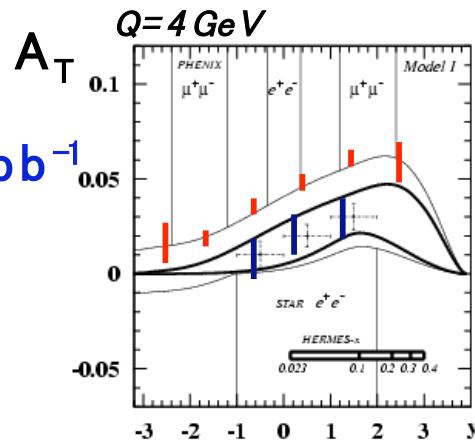
R. Fries, A. Schafer, (2002)

I. Vitev et al, (2006)

- Extremely interesting to access experimentally, understand process dependences and multiple parton interactions high twist / leading twist

Sivers - Asymmetries, A_T in Drell-Yan

STAR for 125 pb^{-1}



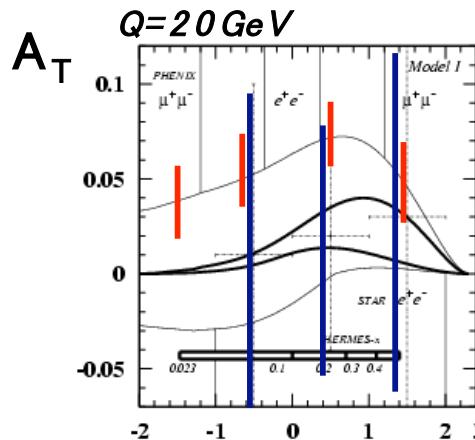
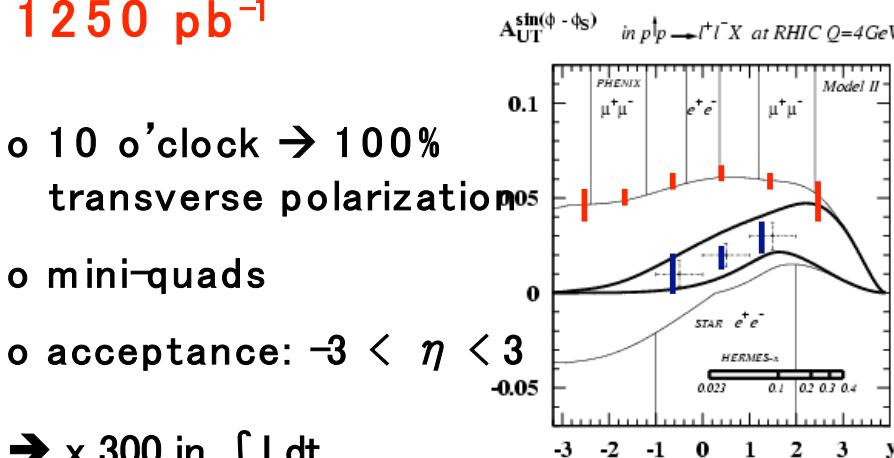
T-SPHINX
 1250 pb^{-1}

- o 10 o'clock $\rightarrow 100\%$ transverse polarization

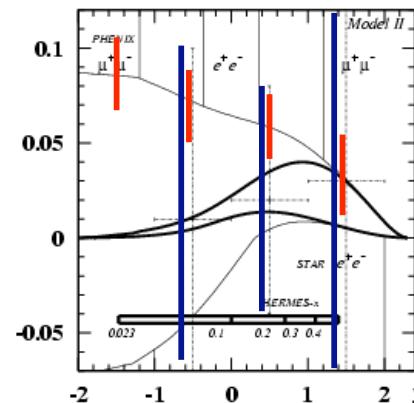
o mini-quads

o acceptance: $-3 < \eta < 3$

$\rightarrow x 300$ in $\int L dt$



$A_{UT}^{\sin(\phi - \phi_S)}$ in $p + p \rightarrow l^+ l^- X$ at RHIC $Q=20\text{ GeV}$

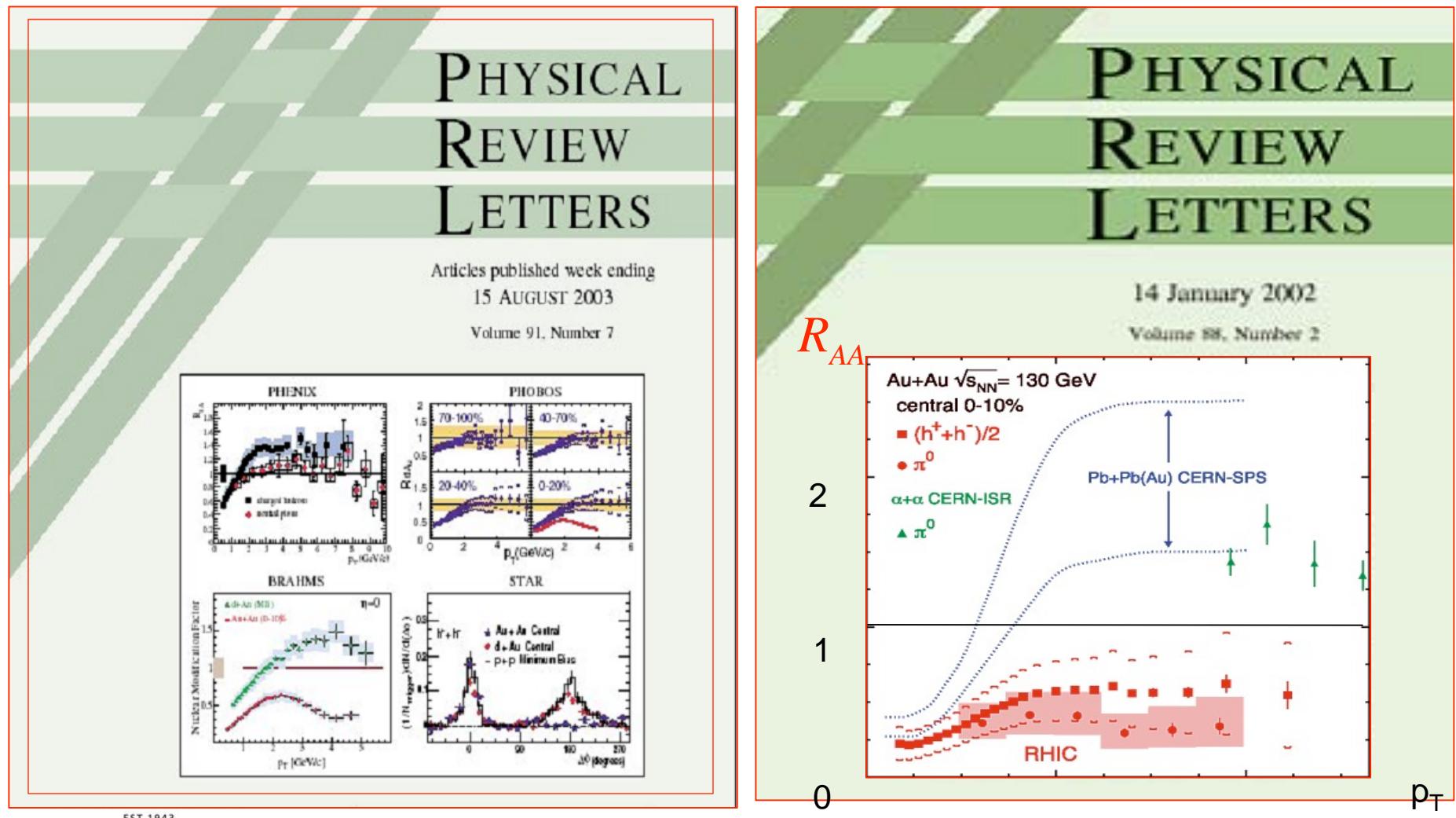


Precision measurement of Sivers distributions!



Ivan Vitev

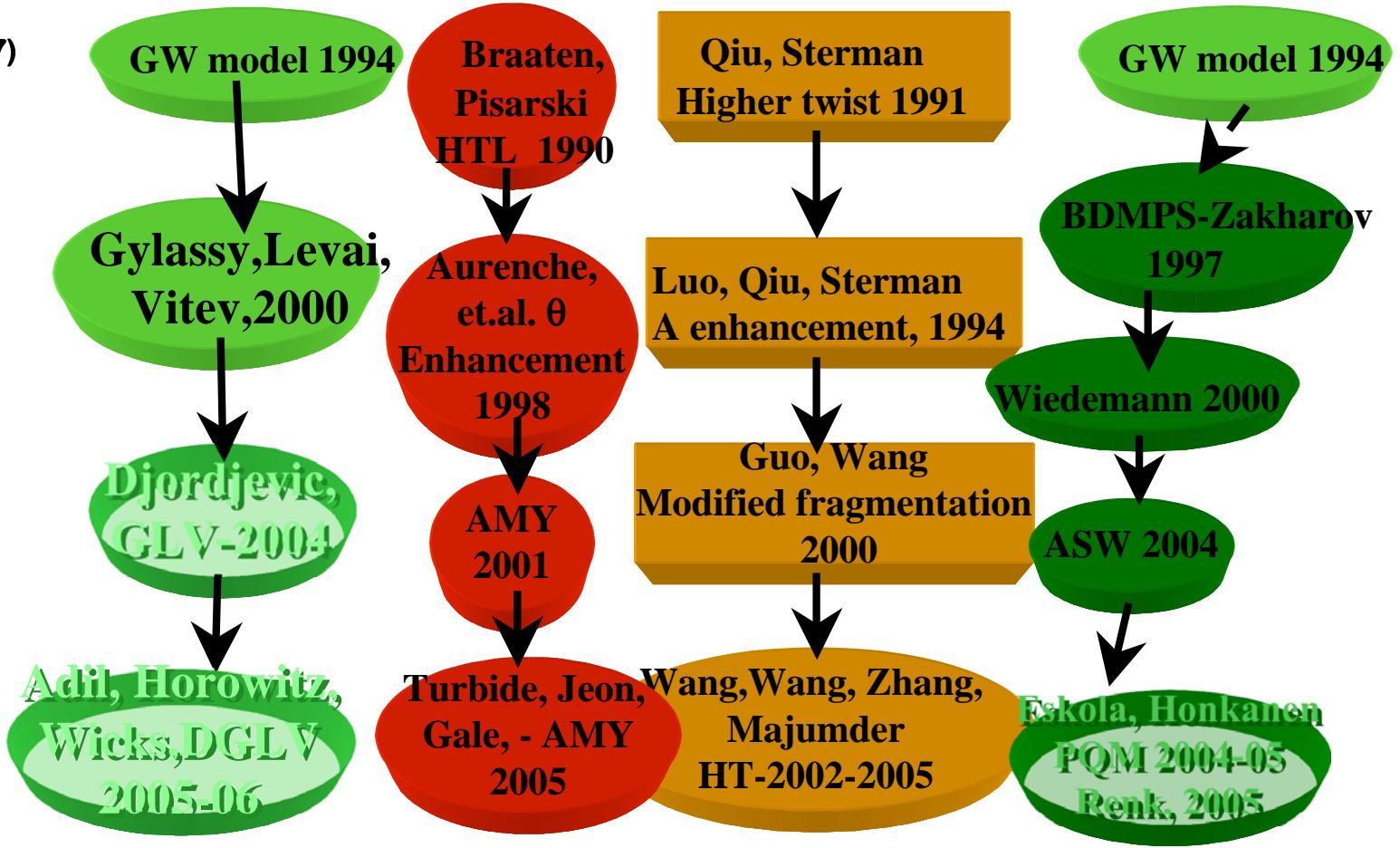
II. Jet Quenching



An Active Field of Heavy Ions

A. Majumder, (2007)

Radiative energy loss formalisms
and subsequent refinements



- Agreement between 3 schemes: GLV, AMY, HT

Energy Loss and Jet Tomography

- Small systems: deep quantum coherence regime (LPM)

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \text{Log} \frac{2E}{\mu^2(L)L} + \dots ,$$

– Static medium

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \text{Log} \frac{2E}{\mu^2(L)L} + \dots ,$$

– 1+1D Bjorken



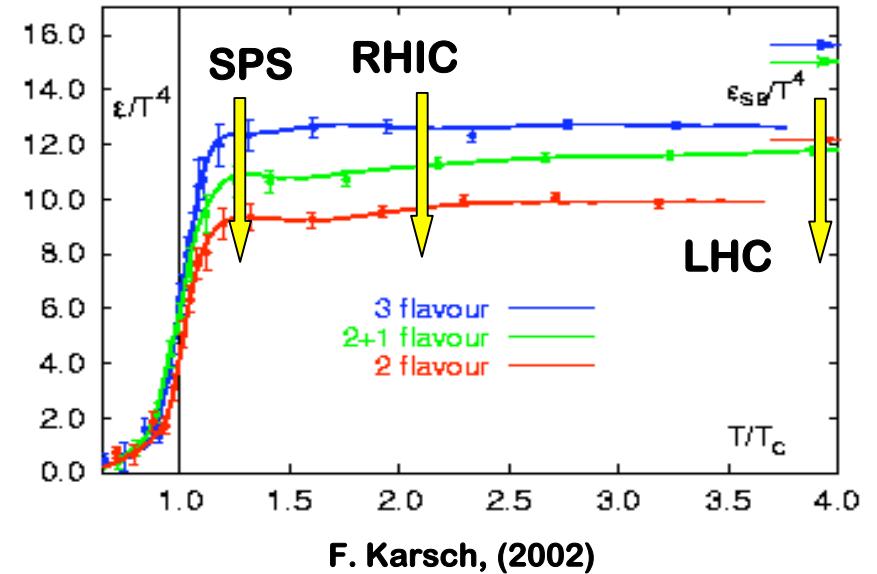
Principles of jet tomography

$$I(r) = e^{-\int_0^r dr' / \lambda_{abs}(r')} = e^{-\int_0^r dr' \rho(r') \sigma(r')}$$

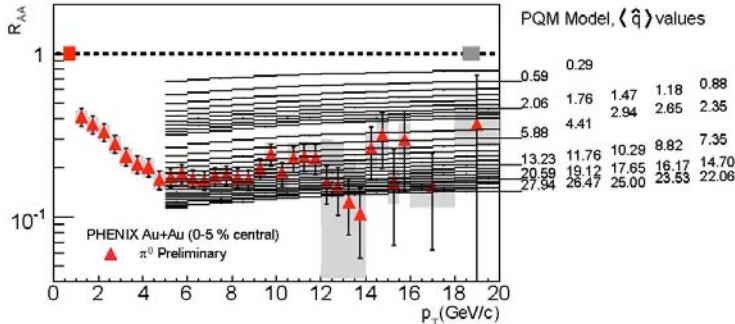
I. Vitev, M. Gyulassy, (2002)

- Goal: characterize the intuitive and easy to interpret characteristics of the QGP

$$T, \varepsilon \sim T^4, \rho \sim T^3$$

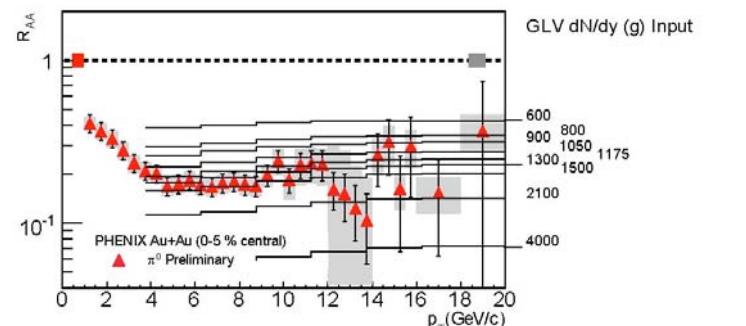
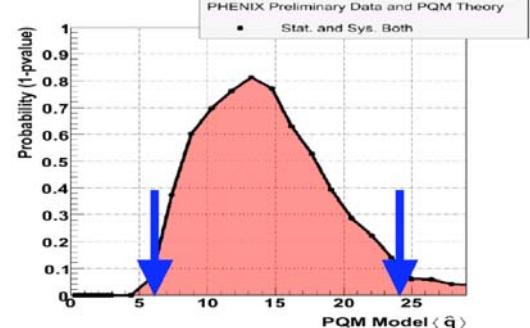


Limitations of the Current High p_T Data



$6 \leq \langle \hat{q} \rangle \leq 24$ GeV $^2/\text{fm}$
(Probability > 10%)

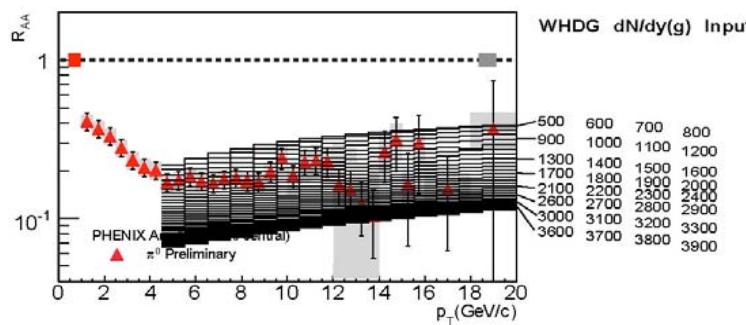
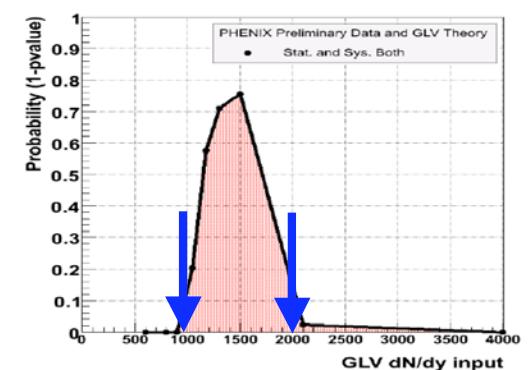
C. Loizides (2006)



$$1000 \leq \frac{dN_g}{dy} \leq 2000$$

(Probability > 10%)

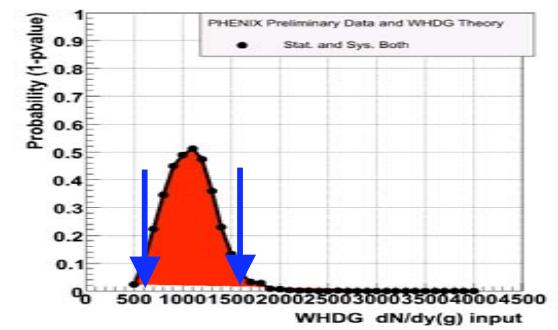
I. Vitev (2006)



$$600 \leq \frac{dN_g}{dy} \leq 1600$$

(Probability > 10%)

W. Horowitz (2006)




Los Alamos
 NATIONAL LABORATORY
EST. 1943

J. Velkovska, J. Negle (2006)



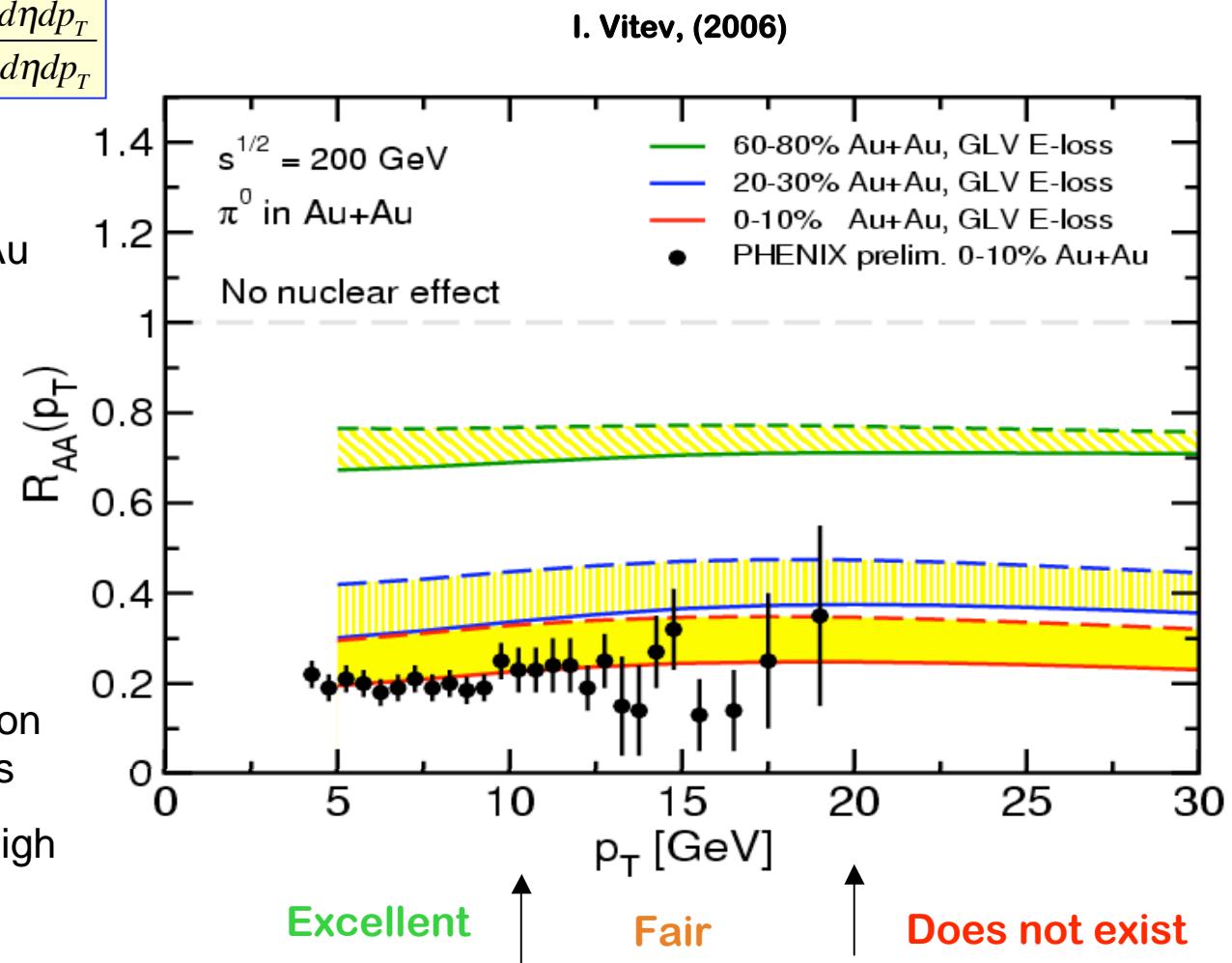
Ivan Vitev

Improvement with RHIC II Luminosity

$$R_{AA}(p_T, \eta) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2\sigma^{AA} / d\eta dp_T}{d^2\sigma^{NN} / d\eta dp_T}$$

Example: ~ 1000 N+N collisions in central Au+Au

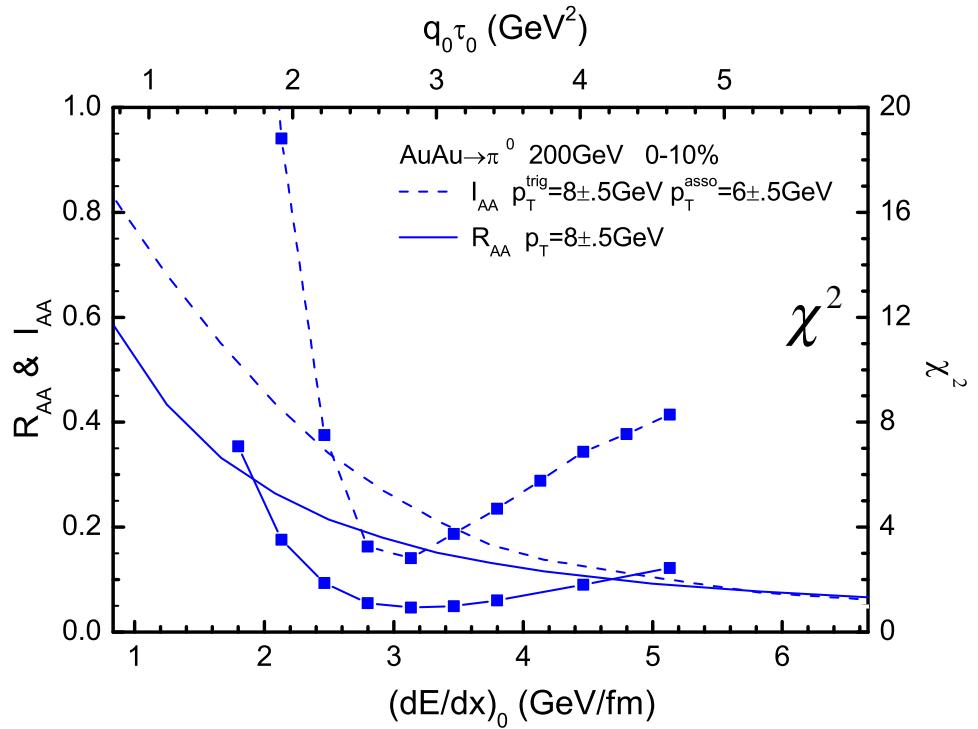
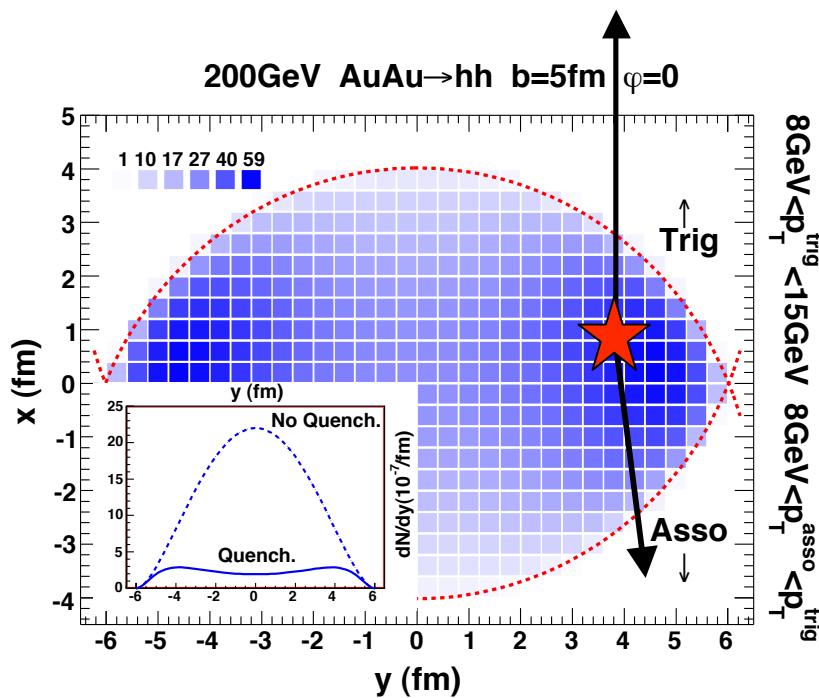
- Data Quality:
RHIC II for precision QGP studies
- Critical for:
 - Precision determination of the QGP properties
 - Exploring the really high p_T region at RHIC



High p_T Di-Hadron Correlations

- Alternative ways to **improve the sensitivity** to the properties of the QGP medium - **di-hadron correlations**
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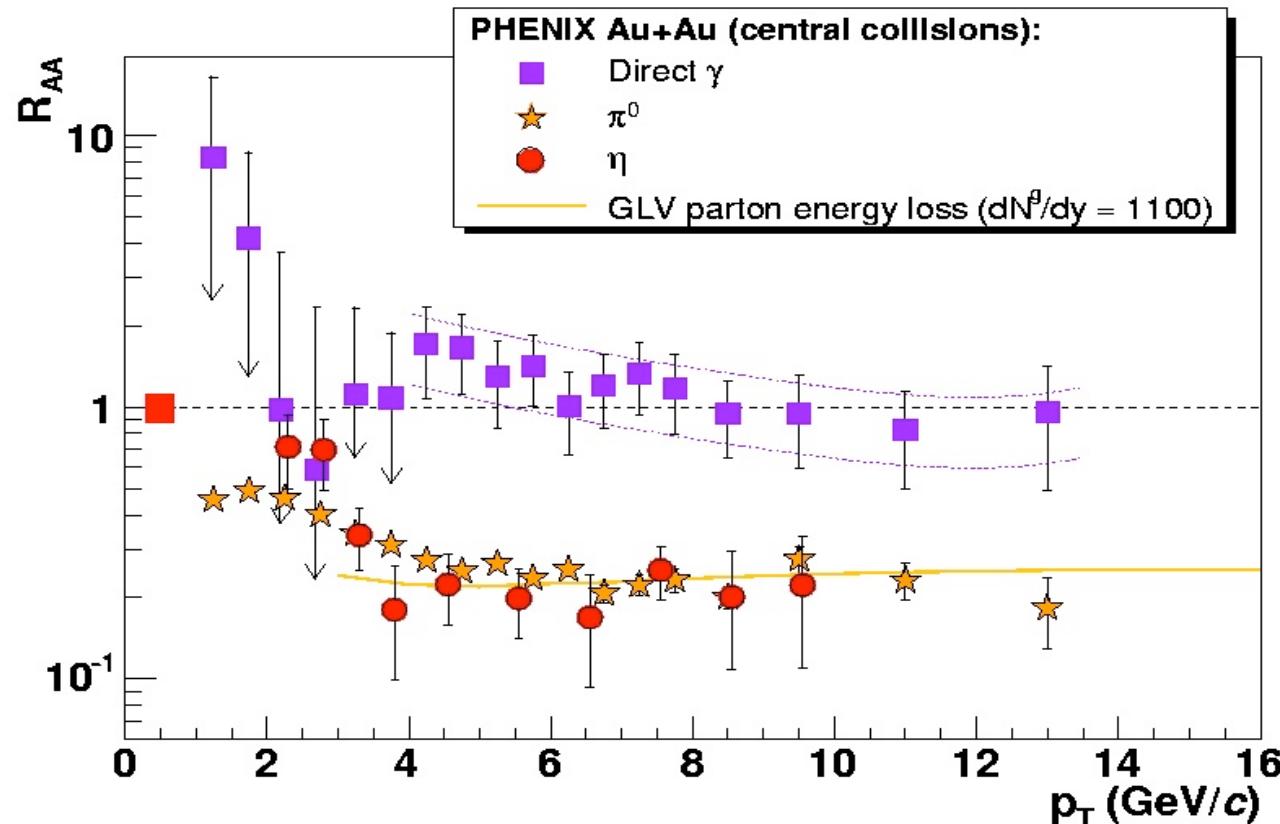
Statistical analysis



J. Owens , X.N. Wang, (2006)

III. Direct Photons

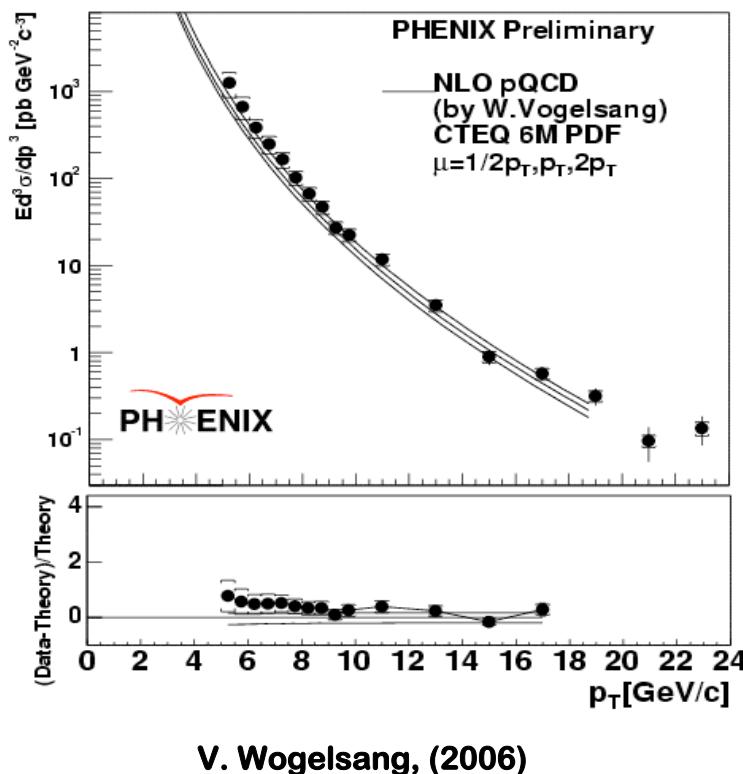
- Direct photons: argued to be only **weakly interacting**



$$d\sigma^{(1)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2) \otimes \frac{1}{2\hat{s}} |M|^2 \otimes D_1(z_1, Q^2)$$

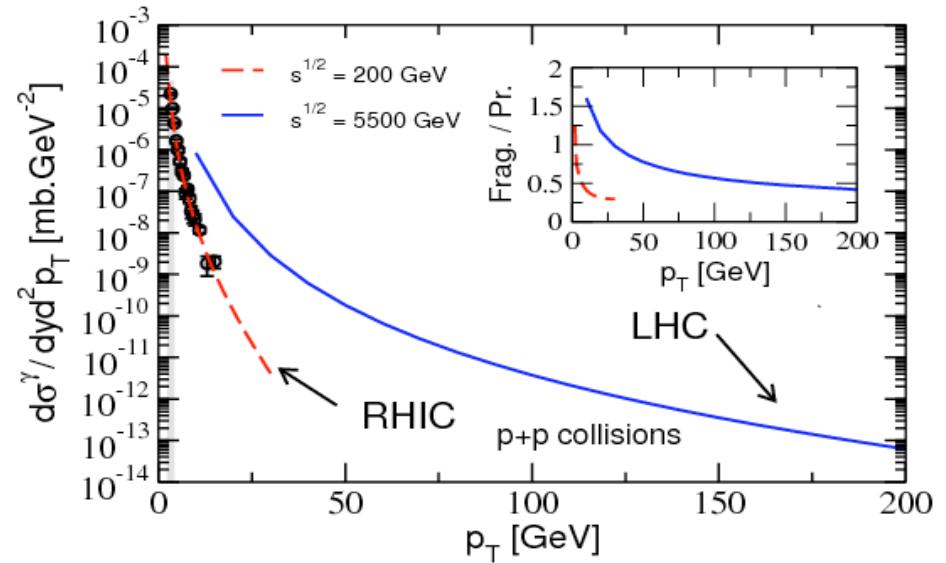
Direct Photon at RHIC (II) versus LHC

- Measurements of direct photon observables, especially in A+A are statistics (and systematics) limited $|M|^2 \sim \alpha_s \alpha_{em}$



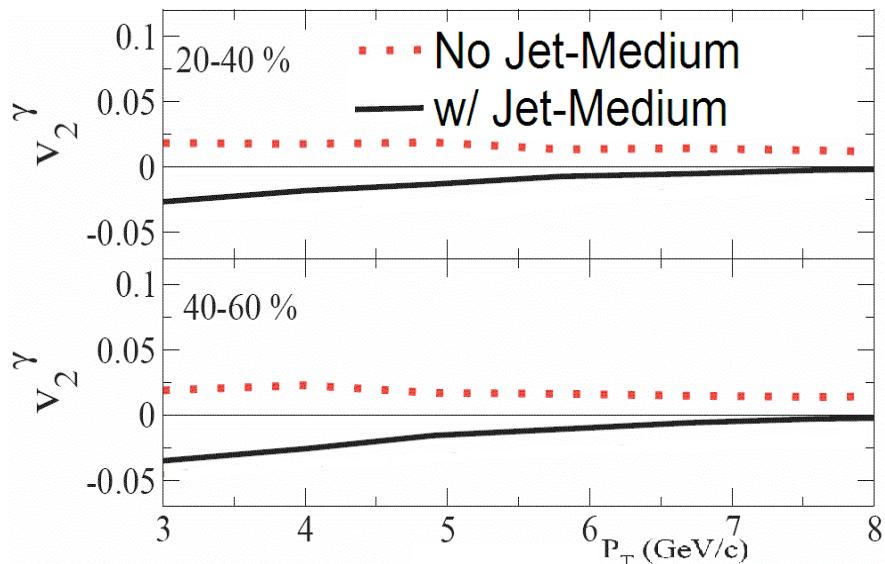
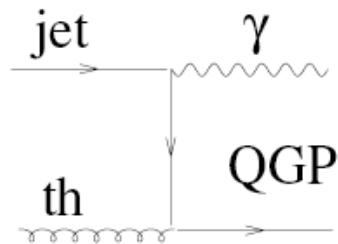
$$\begin{aligned} \text{Prompt photons} \quad D_{\gamma/\gamma}(z) &= \delta(z-1) \\ + \quad \text{Fragmentation photons} \quad \{ & \begin{aligned} D_{\gamma/q}(z) \\ D_{\gamma/g}(z) \end{aligned} \end{aligned}$$

$$R = \frac{d\sigma / dy d^2 p_T (\text{fragmentation})}{d\sigma / dy d^2 p_T (\text{prompt})}$$



QGP Induced Bremsstrahlung and Jet Conversion

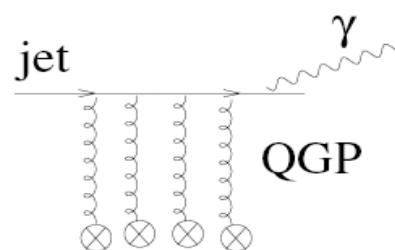
- Jet conversion



S. Turbide et al., (2005)

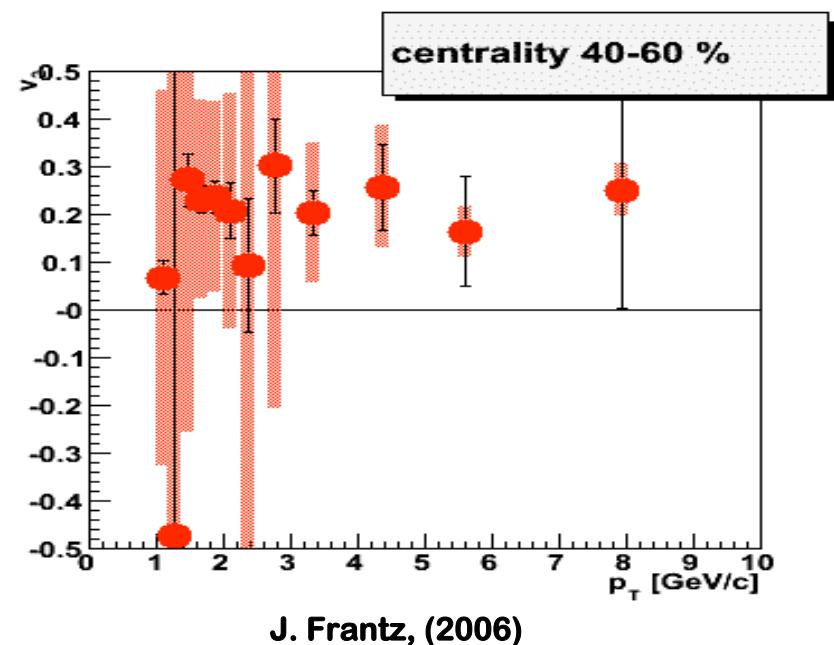
R. Fries et al., (2003)

- Photon bremsstrahlung



Negative v_2

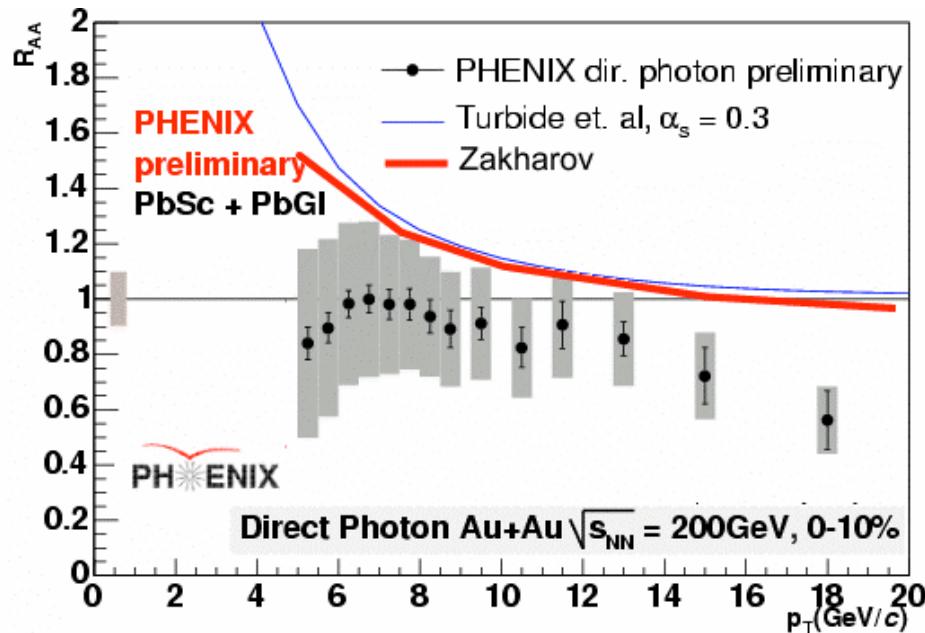
$$\frac{dN^h}{dy d^2 p_T d\phi} = \frac{1}{2\pi} \frac{dN^h}{dy d^2 p_T} (1 + 2v_2(\cos 2\phi) + \dots)$$



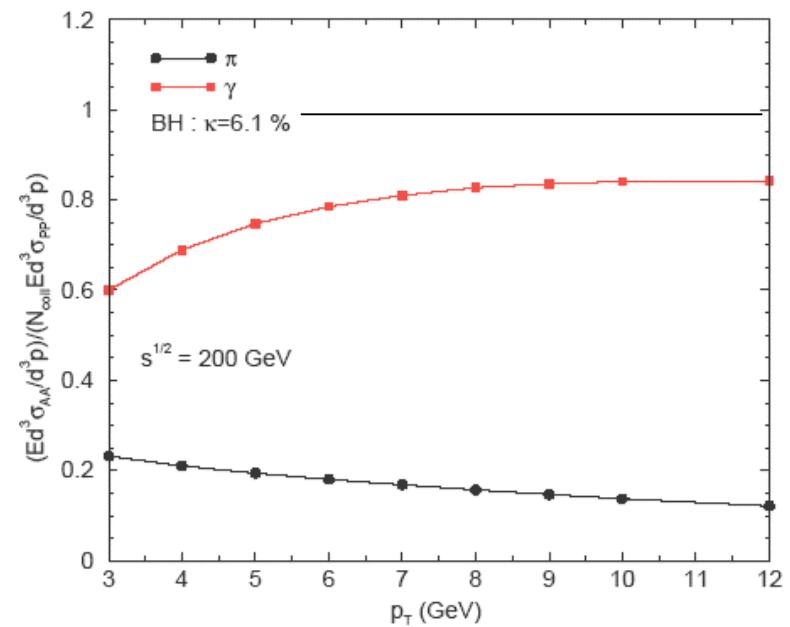
- Better statistics is needed to exclude theoretical models

Single Inclusive Photon Modification

Photon bremsstrahlung, jet conversion



Energy loss of quarks - fragmentation γ



S. Jeon, J. Jalilian-Marian, I. Sarcevic, (2002)

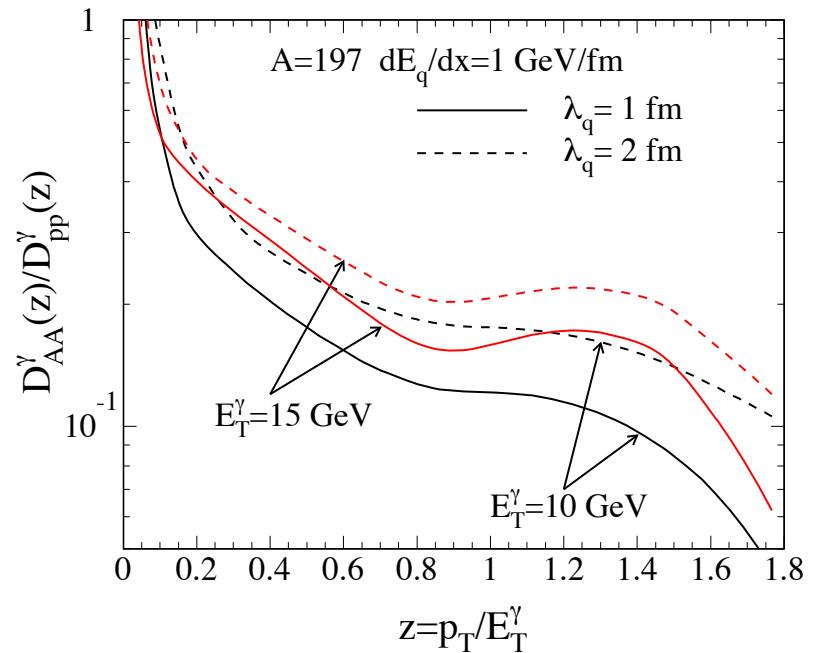
- Lead to the same conclusion: data is suggestive (but not conclusive) of quenching of fragmentation photons

We have to rethink the “golden” energy loss channel

Photon-Hadron Correlations

- Original idea to determine the energy loss of quarks

$$I_{AA}(p_T) = \frac{\left[\frac{d\sigma^{(2)}}{dp_{T1}dp_{T2}} / \frac{d\sigma^{(1)}}{dp_{T1}} \right]_{AA}}{\left[\frac{d\sigma^{(2)}}{dp_{T1}dp_{T2}} / \frac{d\sigma^{(1)}}{dp_{T1}} \right]_{pp}} \approx \frac{D_{AA}^\gamma(z = p_T / E_\gamma)}{D_{pp}(z = p_T / E_\gamma)}$$



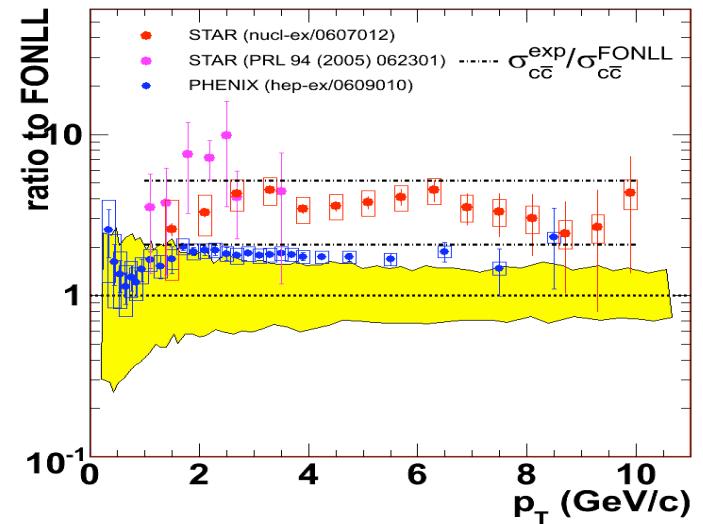
X. Wang, H. Zhang, I. Sacevic (1996) F. Arleo, (2006)

In light of the recent results

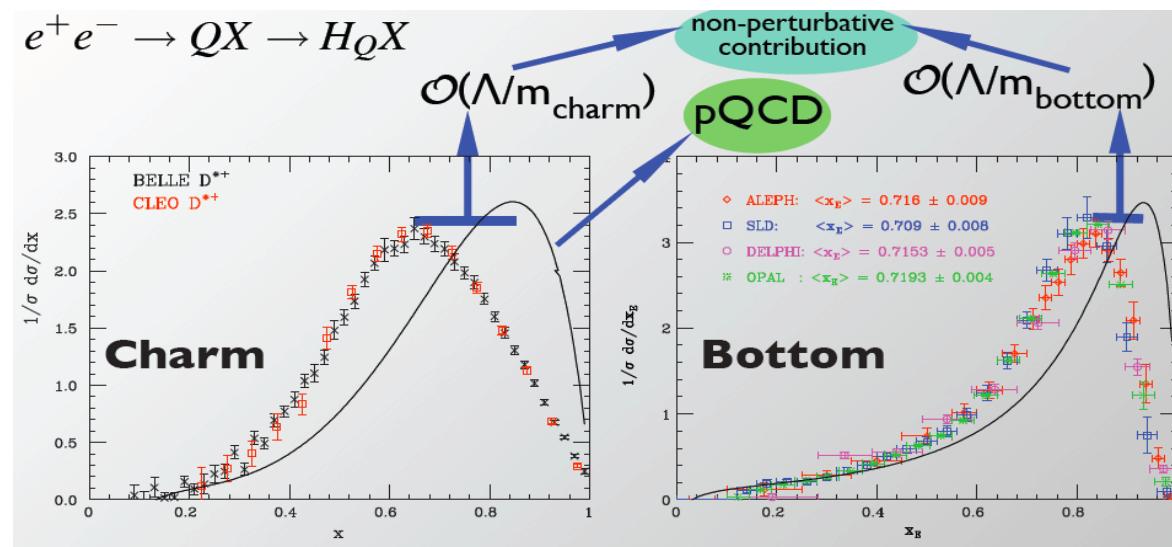
- While this still remains the method to most directly access the energy loss of quarks it is **not** as **bias free** as previously thought
- Not only **gamma-jet** but also **single inclusive hadron measurements** are needed

IV. Heavy Flavor

- Expected to be perturbatively computable
- Fixed order, next-to-leading log calculations
- Systematic deviations for non-photonic electrons between the calculation, the data and the two experiments
- How would it compare to direct measurements of D-, B-mesons?

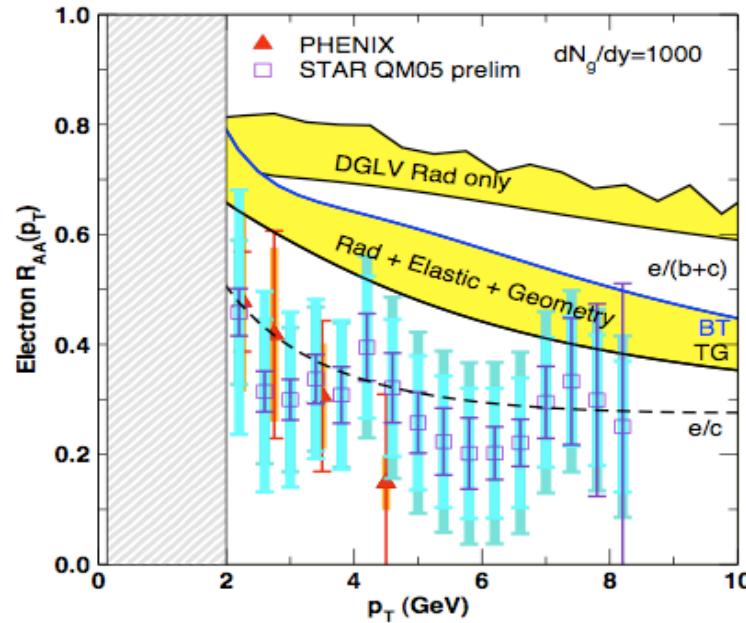


M.Cacciari, P. Nason
R. Vogt (2006)



Non-Photonic Electron / Heavy Flavor Quenching

Radiative and collisional energy loss



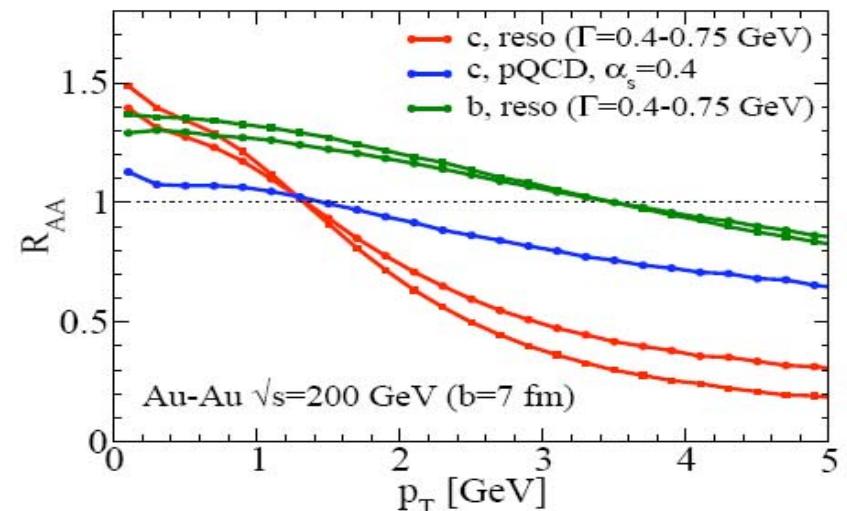
S. Wicks et al., (2005)

N. Armesto et al., (2006)

- Ratio: $\Delta E_{coll.} / \Delta E_{rad.}$
- Opacity L / λ_g of the QGP

Langevin simulation of heavy quark diffusion

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i} \left(p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ij}(p,t) \right) \partial f(p,t)$$



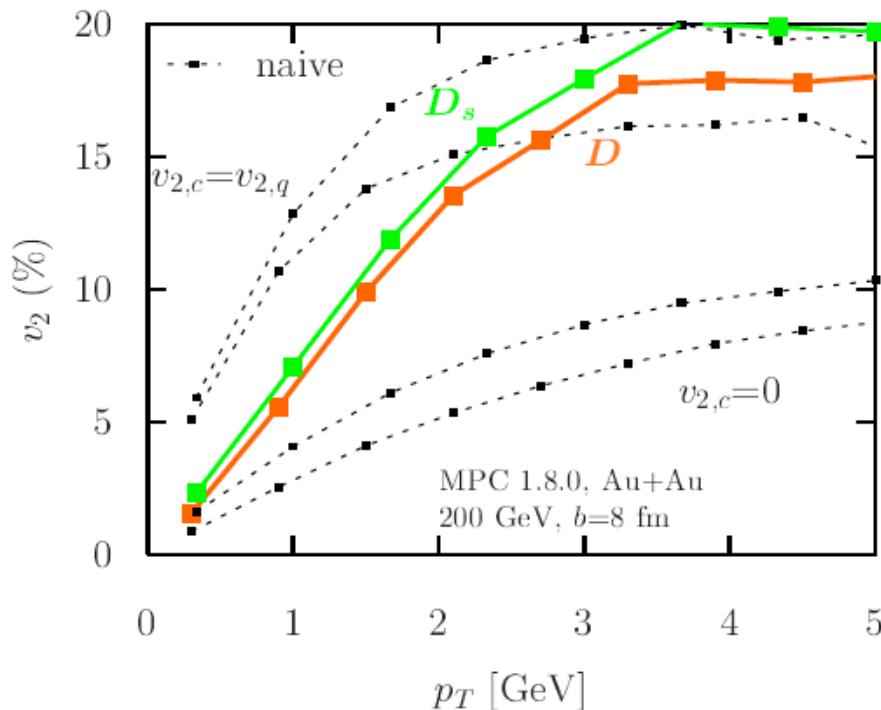
H. van Hees, R. Rapp, (2005) G. Moore, D.Teaney (2005)

- Diffusion coefficient D and eventually η / s
- Existence of heavy resonances near T_c in the QGP

Heavy Flavor Elliptic Flow and Suppression

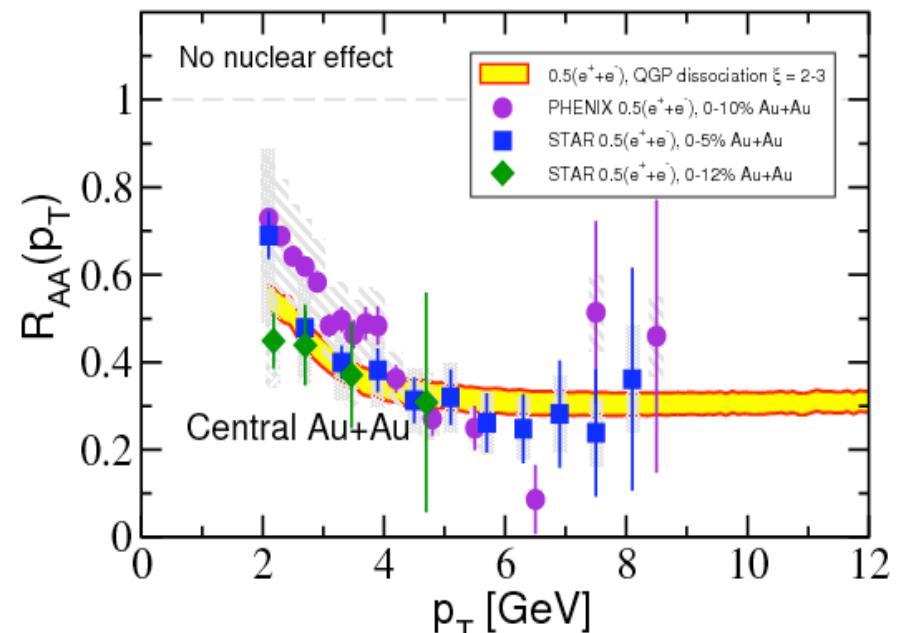
Test coalescence model fits to the v_2 of light hadrons via heavy flavor

$$v_{2,B}(x, p_T) \approx \sum_{i=\alpha,\beta,\gamma} v_{2,i}(x, p_{T,i}), \quad v_{2,M}(x, p_T) \approx \sum_{i=\alpha,\beta} v_{2,i}(x, p_{T,i})$$



Understand the structure of mesons
light cone wave functions

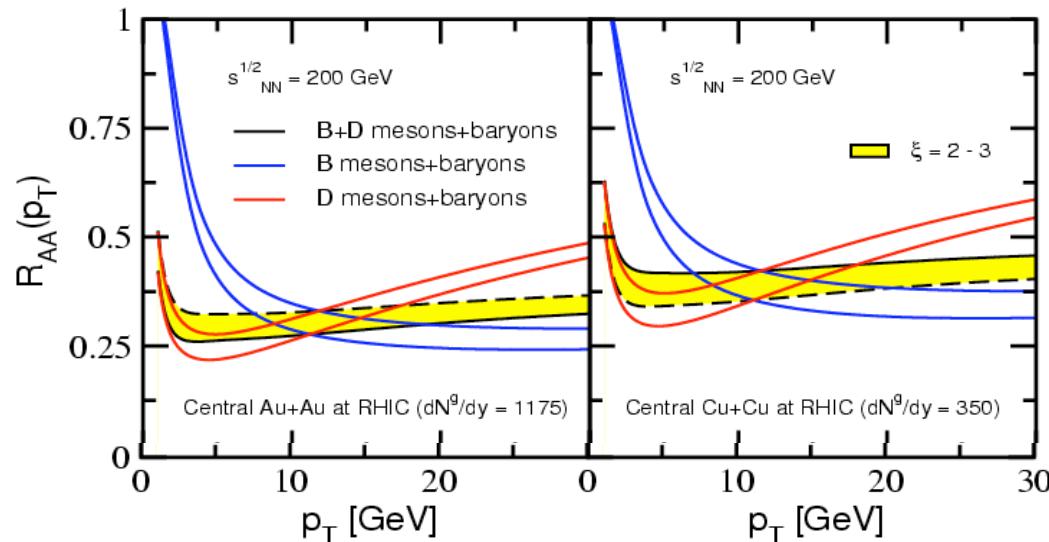
Sensitive to the opacity of the QGP
and its formation time τ_0



The Path Forward

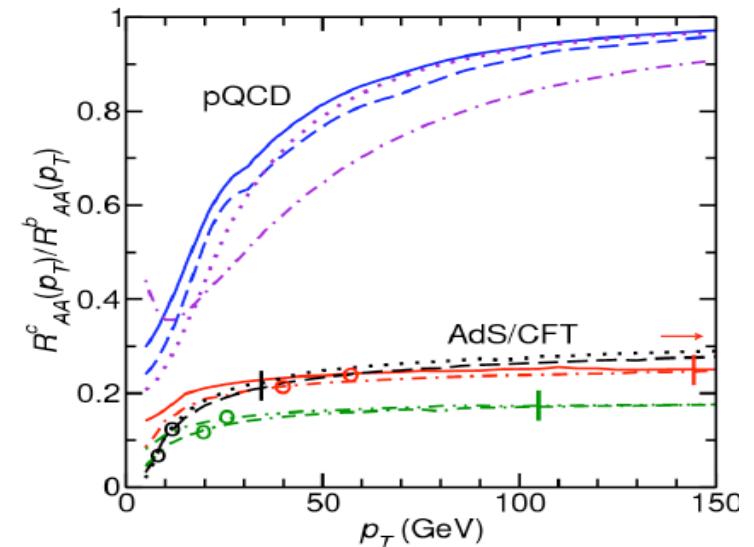
- An interesting idea \neq valid physics explanation
- To understand heavy flavor modification in the QGP we need **direct and separate measurements** of D- and B-mesons, **excellent statistics**

Measurable at RHIC



A.Adil, I.Vitev, (2006)

Measurable at the LHC



W.Horowitz, M. Gyulassy, (2007)



$$\frac{R_{AA}^c(p_T)}{R_{AA}^b(p_T)} = 1$$

Meson
dissociation

10-15

PQCD,
Transport

50-100

String theory
AdS/CFT

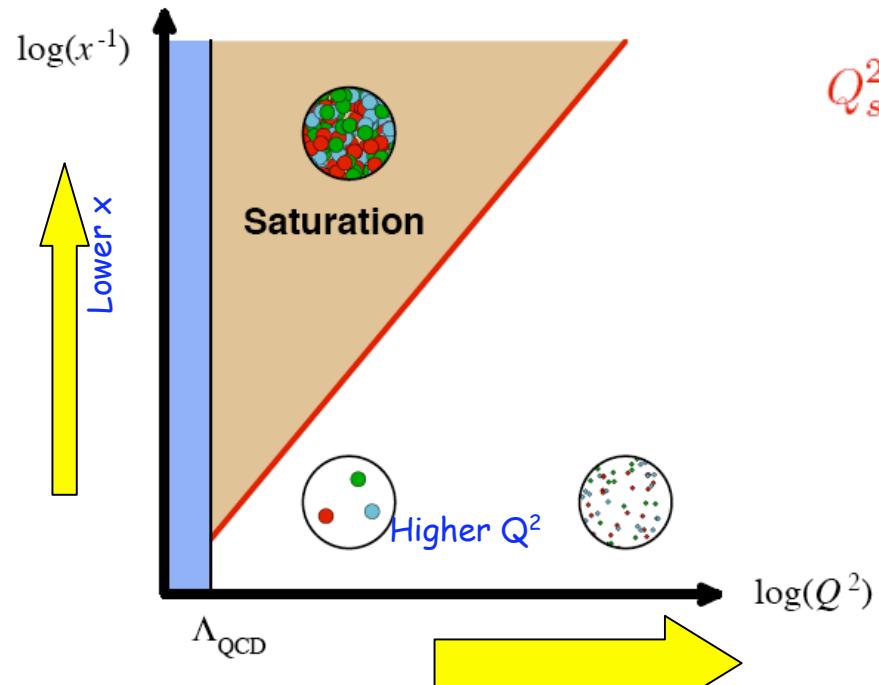
Never

$p_T [\text{GeV}]$



Ivan Vitev

V. Forward Rapidity Physics: Saturation Models



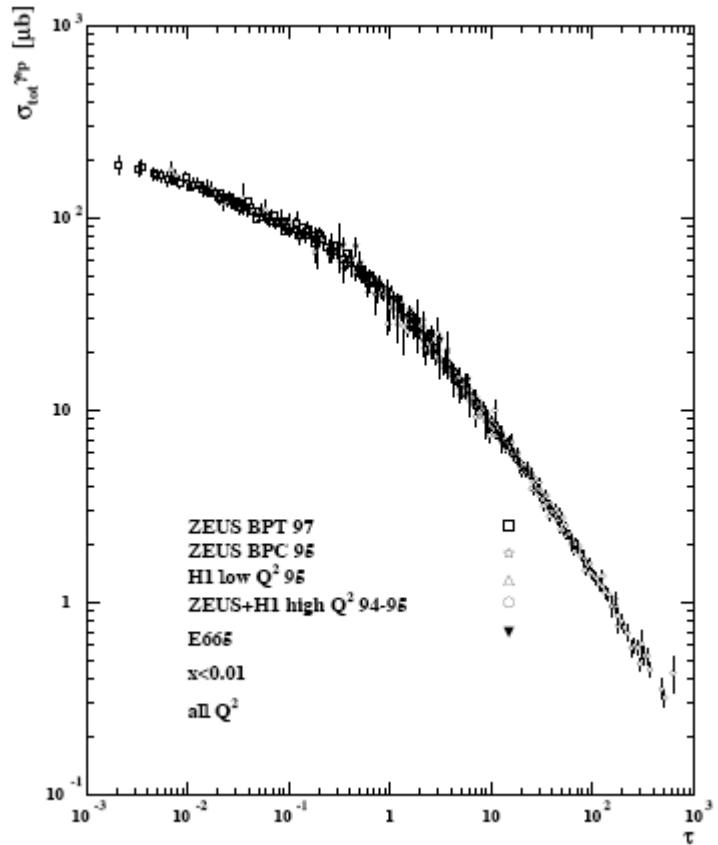
A. Mueller, J. Qiu, (1986)

- Nonlinear gluon evolution **2-to-1 processes**

L. McLerran, R. Venugopalan, (1994)

- Classical Yang-Mills fields

$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$



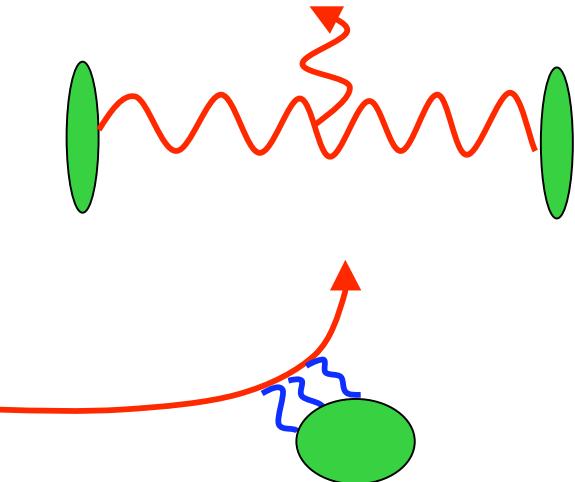
Golec-Biernat, Wusthof, (2000)

Forward Rapidity Suppression

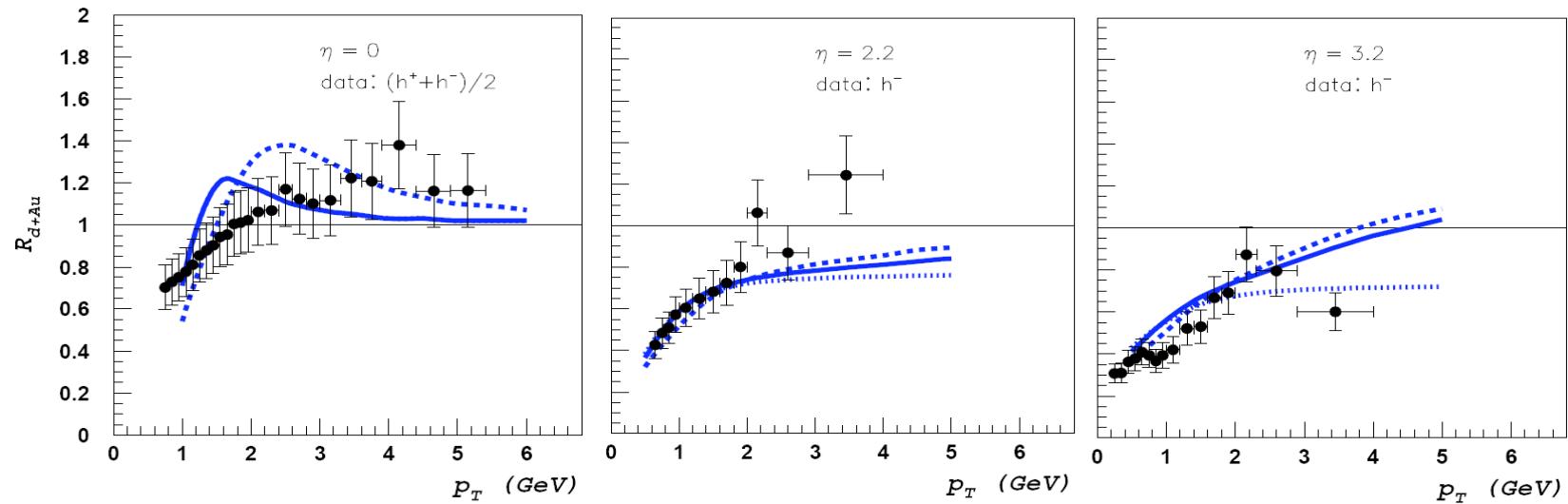
- Particle production via 2 to 1 processes (**monojets**)

$$\frac{dN_g}{dy d^2x_T dp_T} \propto \frac{1}{p_T} \int d^2k_T \phi_A(x_1, \frac{\vec{p}_T + \vec{k}_T}{2}) \phi_B(x_2, \frac{\vec{p}_T - \vec{k}_T}{2})$$

Gribov, Levin, Rishkin, Phys. Rep. (1980)



- Elaborated to include **quark scattering on CGC**
- Brahms hadron forward suppression pattern



D. Kharzeev, Y. Kovchegov, K. Tuchin, (2004)

Particle Production Mechanism

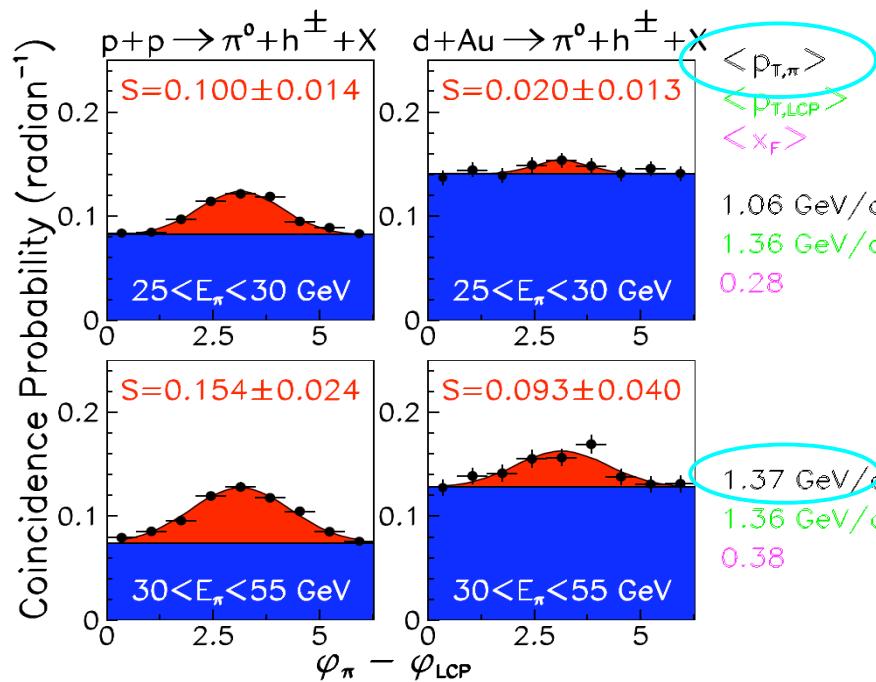
$$I_{d+Au}^c = \frac{N_{asso}^{d+Au}}{N_{trig}^{d+Au}} = \frac{N_{asso}^{p+p}}{N_{trig}^{p+p}}$$

Di-jets:

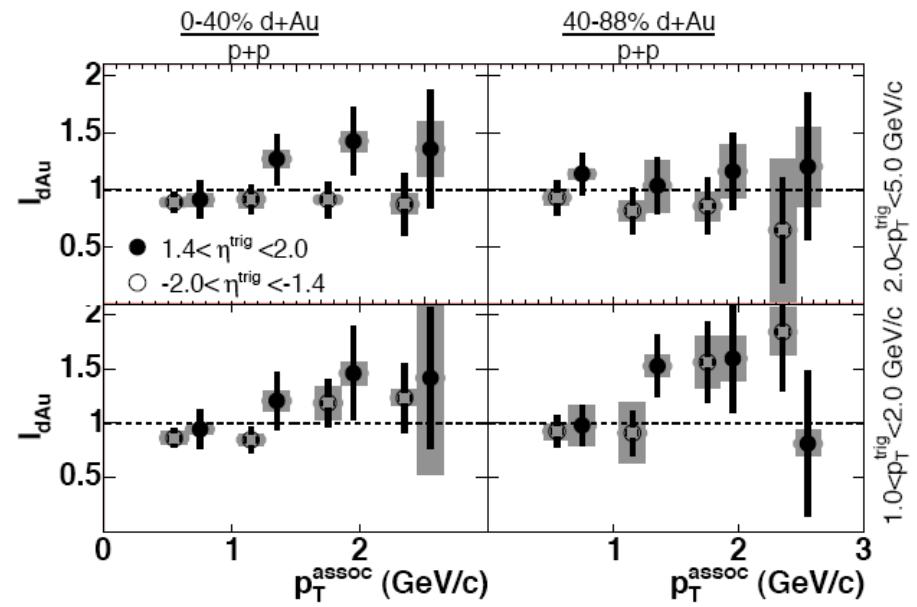
$$\frac{d\sigma_{NN}^{h_1 h_2}}{dy_1 dy_2 dp_{T1} p_{T2}} = 2\pi \sum_{abcd} \int_{z_1 \text{ min}}^1 dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\bar{x}_a)\phi(\bar{x}_b)}{\bar{x}_a \bar{x}_b} \frac{\alpha_s^2}{S^2} \left| \bar{M}_{ab \rightarrow cd}^2 \right|$$

Monojets:

$$\frac{dN_g}{dy d^2x_T dp_T} \propto \frac{1}{p_T} \int d^2k_T \phi_A(x_1, \frac{\vec{p}_T + \vec{k}_T}{2}) \phi_B(x_2, \frac{\vec{p}_T - \vec{k}_T}{2})$$



L. Bland et al., (2005)

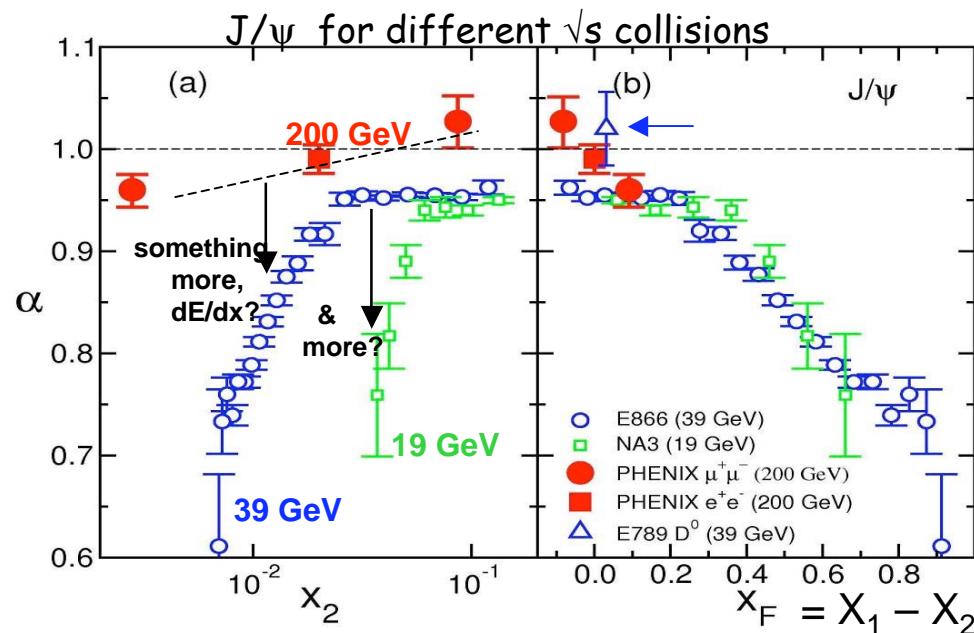


C. Zhang et al., (2006)

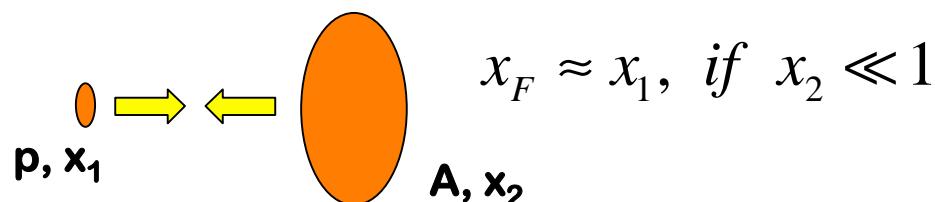
- Suggestive of di-jet production mechanism

Evidence for Energy Loss in Cold Nuclei

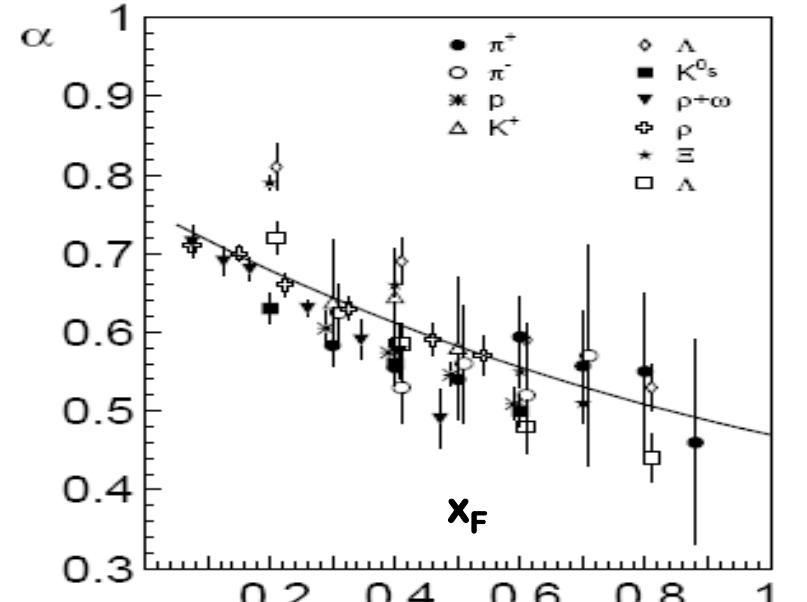
Cross section scaling: $\sigma_A = A^\alpha \sigma_N$



M. Leitch et al. PHENIX, EA866 and NA3 data



Universal scaling

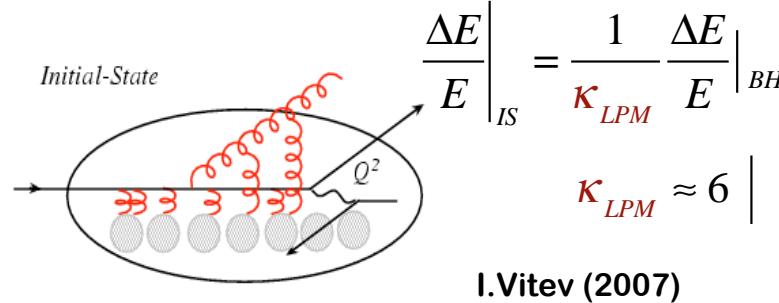


B.Kopeliovich et al. (2006)

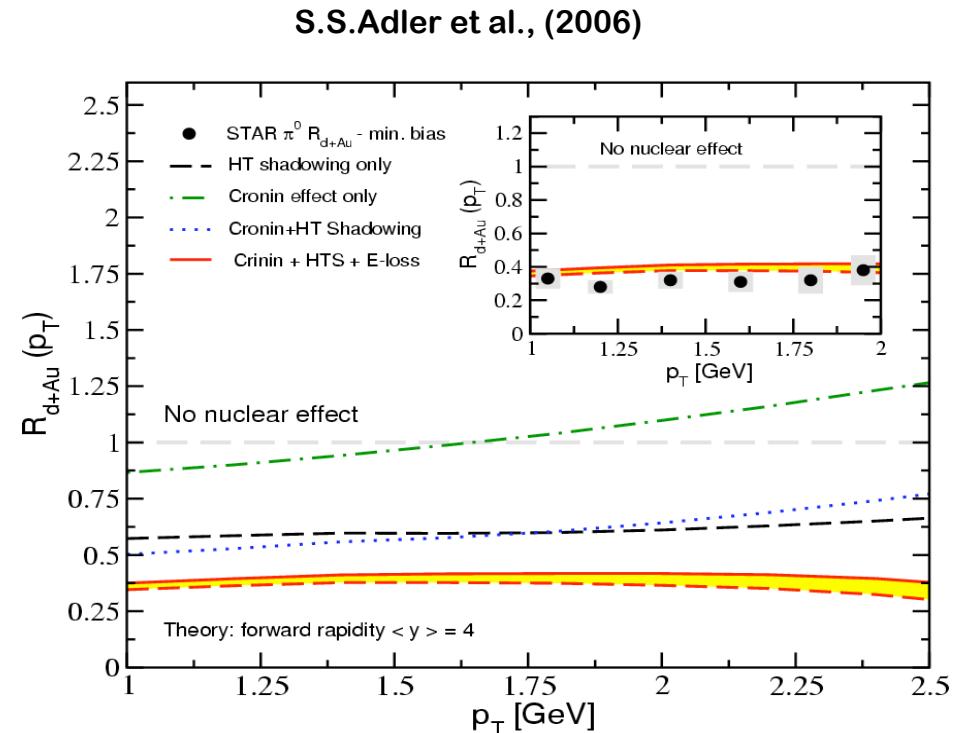
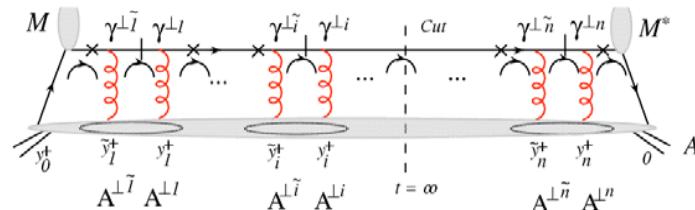
- Energy loss is a dominant mechanism in the forward rapidity / large x_F suppression (Sudakov suppression)

Nuclear Effects at Forward Rapidity

- Theoretical developments in parton E-loss :



- Original incoherent result:



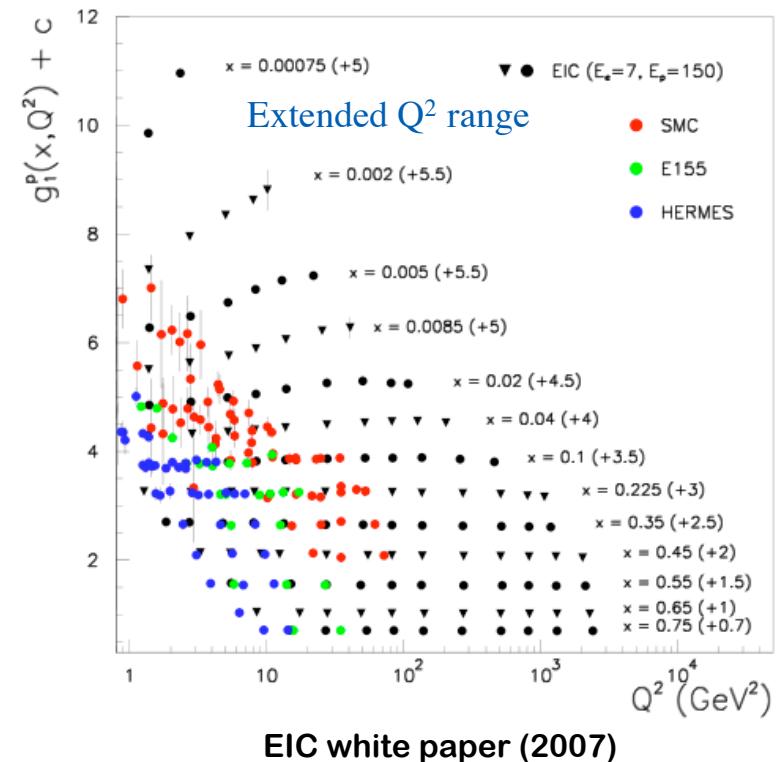
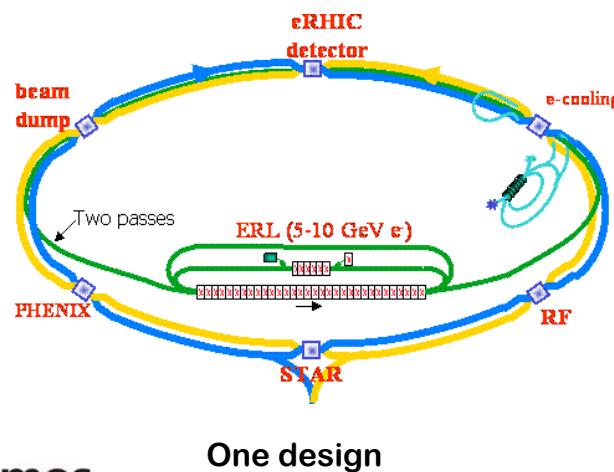
- Note the different contributions to an overall suppression effect

Coexistence with ongoing effort: E906 Fermilab - the first precise determination of quark energy loss in nuclei

From RHIC II to eRHIC

Forward rapidity physics is a **complex superposition** of nuclear effects: **Cronin, energy loss / nuclear stopping, and shadowing / gluon saturation** effects

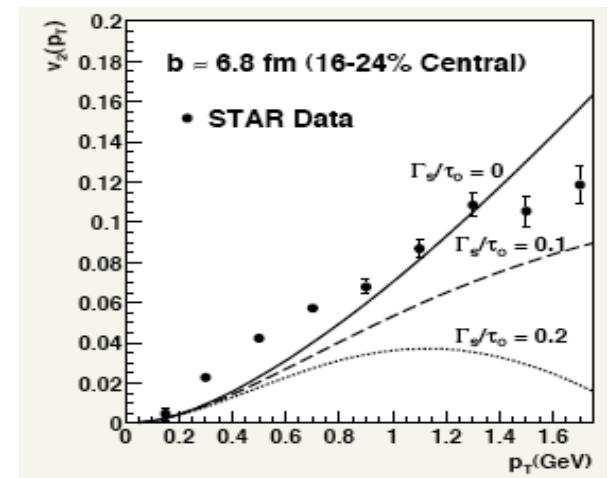
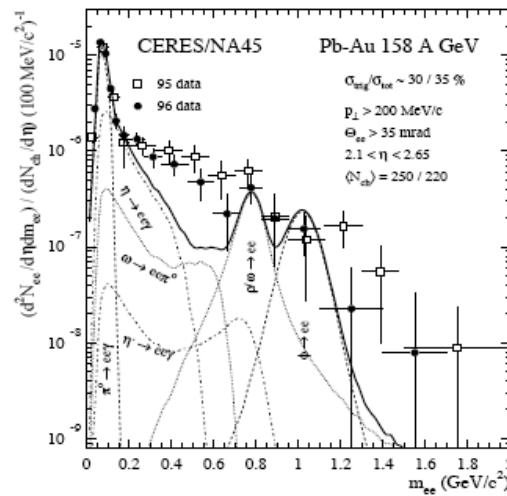
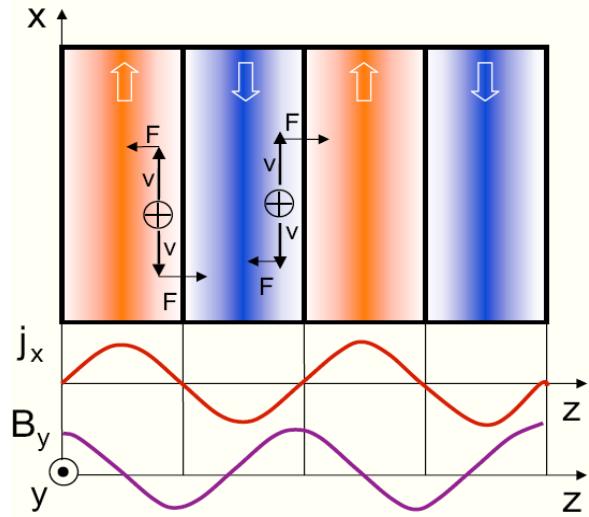
- To begin to disentangle **initial-** versus **final-state** effects at RHIC one needs weakly interacting probes such as **Drell-Yan** $q + \bar{q} \rightarrow \mu^+ + \mu^-$ (require high luminosity)
- To understand the origin of **nuclear shadowing** and explore **non-linear small-x** physics **DIS at eRHIC is needed**



Other Compelling Physics Questions

To benefit from detector upgrades / RHIC II

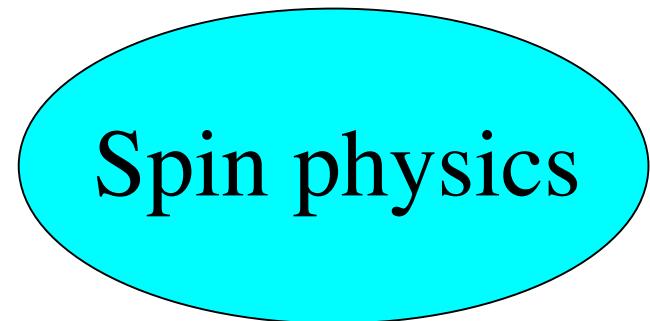
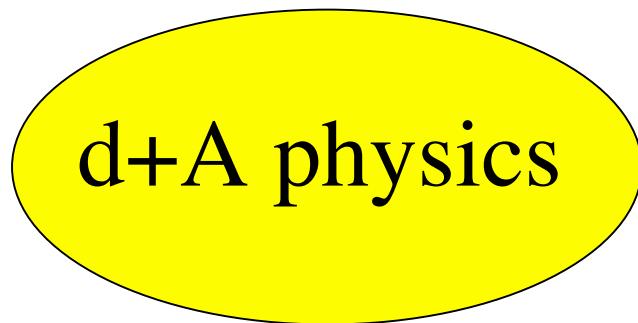
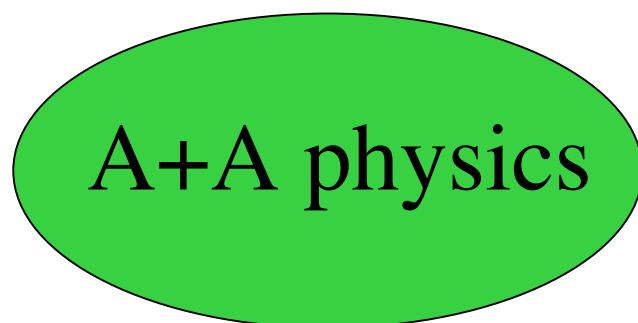
- What is the **thermalization mechanism** of the quark-gluon plasma ?
- What is the **viscosity** of the quark-gluon plasma ?
How **imperfect** is the “perfect fluid”?
- What is the **plasma response** to jets?
- Di-leptons and **chiral symmetry restoration**?



B. Jacak (2007)

Summary I

Fundamental thermal field theory, many-body QCD at high energies, small-x physics, and the origin of spin



Summary II

Specific examples given

Spin physics

Longitudinal and transverse spin observables, Sivers

The A+A program with RHIC upgrades / RHIC II

- Precision physics with high- p_T jets, high- p_T particle correlations
- Direct measurements of open heavy flavor
- Direct photon physics, photon-hadron correlations

The p+A program with RHIC upgrades / RHIC II

- Possibility for gluon saturation physics at forward rapidity, eRHIC case
- Longitudinal dynamics, energy loss, dynamical shadowing

Other compelling questions to benefit from RHIC upgrades / RHIC II

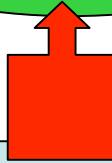
- Thermalization of the QGP, viscosity, elliptic flow, quarkonia, dileptons ...

Rare Hard Probes of the QGP

Heavy Flavor

Direct Photons

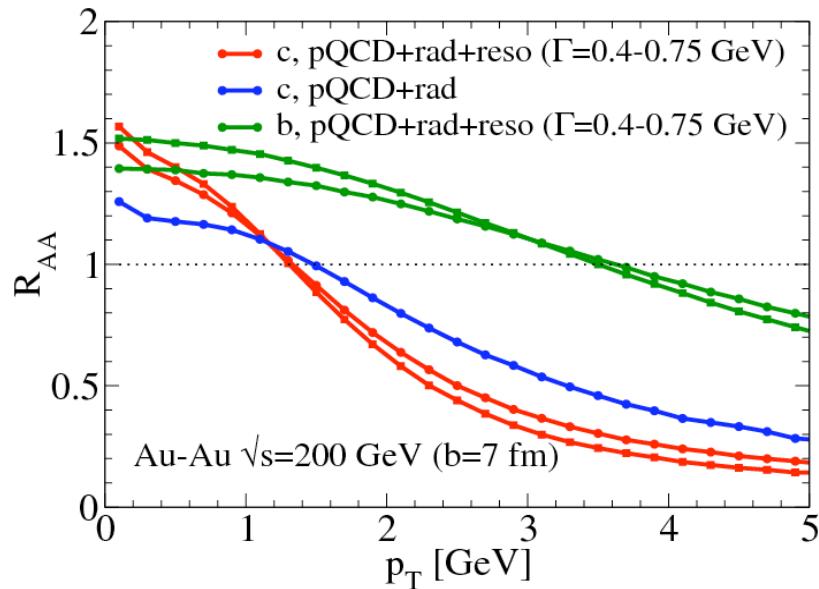
A+A physics



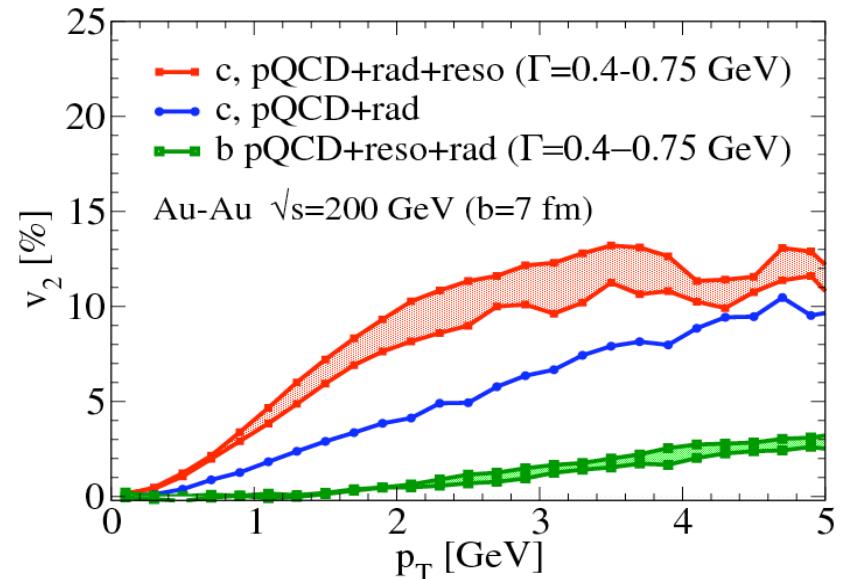
Assisted by precise jet tomography of the QGP

Transport + Quenching Approach

Numerical results for c, b diffusion



Elliptic flow (azimuthal asymmetry)



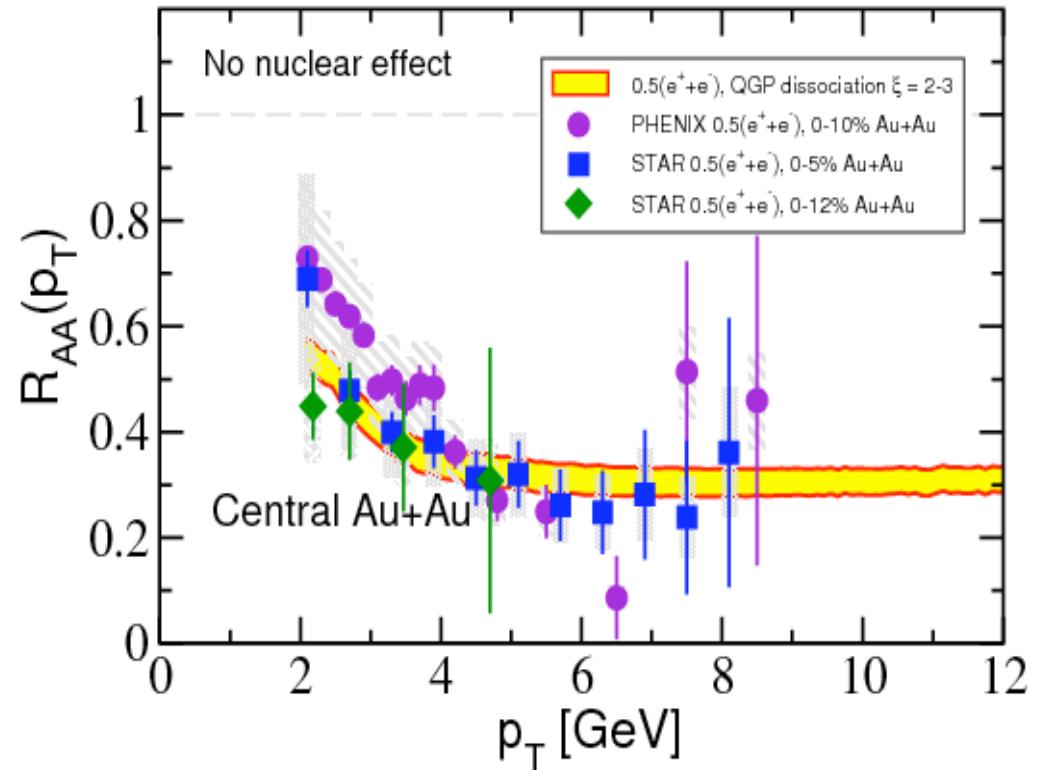
- The suppression and v_2 are **large** with E-loss and q-resonance interactions combined
 - Normal hierarchy:** c quarks are significantly more suppressed than b -quarks
- Measurements can constrain the QGP parameters in a **correlated** way

$$\left[\varepsilon_0 \approx 15 \text{ GeV/fm}^3, \tau_0 \approx 0.6 \text{ fm}, T_0 \approx 370 \text{ MeV}, dN^g / dy \approx 1000 \right]$$

Quenching of Non-Photonic Electrons

- Full semi-leptonic decays of C- and B- mesons and baryons included. PDG branching fractions and kinematics. PYTHIA event generator

$$R_{AA}^{e^\pm}(p_T) = \frac{d\sigma_{AA}^{e^\pm} / dy d^2 p_T}{\langle N_{\text{coll}} \rangle d\sigma_{pp}^{e^\pm} / dy d^2 p_T}$$



- B-mesons are included. They give a major contribution to $(e^+ + e^-)$

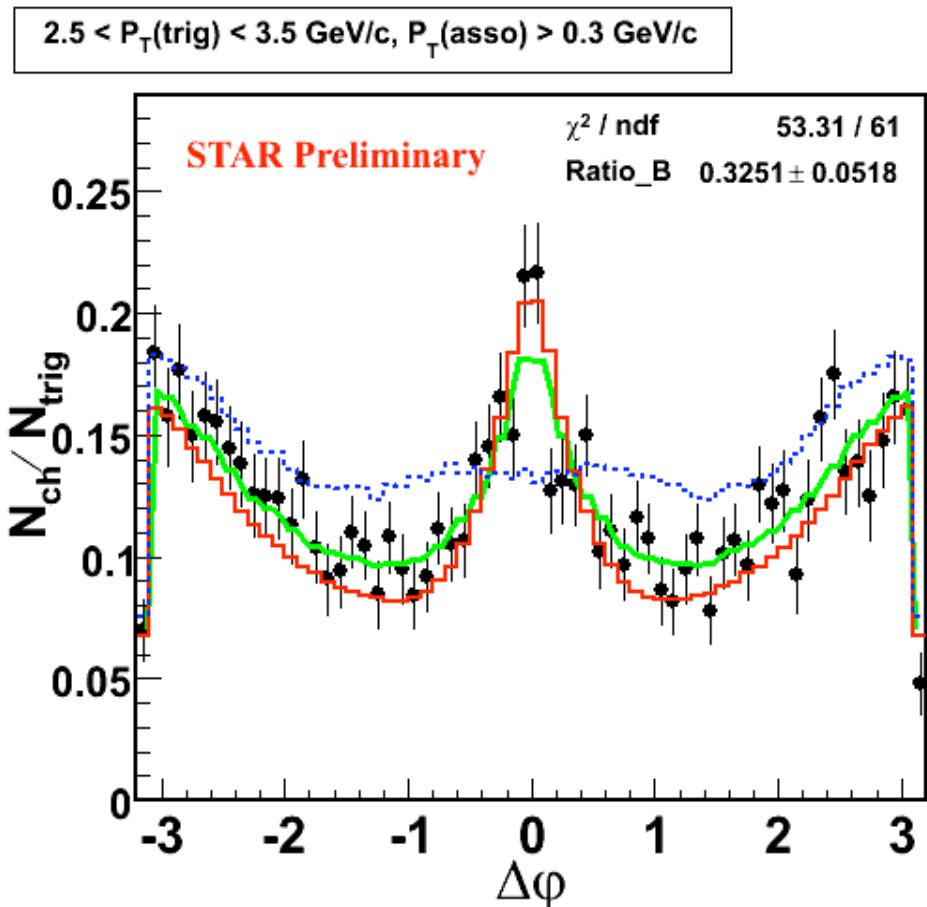
Note on applicability

D-, B-mesons to $R_{AA}(D) = R_{AA}(B)$
 $(e^+ + e^-)$ to 25 GeV

e-h correlations in p+p: bottom vs. charm

See Xiaoyan Lin's talk for STAR

- Understand charm and bottom production is a key point to understand suppression and flow
- Direct measurement is very complicated
- One possible idea: electron-hadron correlations
 - Near side peak dominated by decay kinematics
- Preliminary e-h correlations from p+p collisions in STAR
 - Extract relative bottom contribution for different electrons p_T

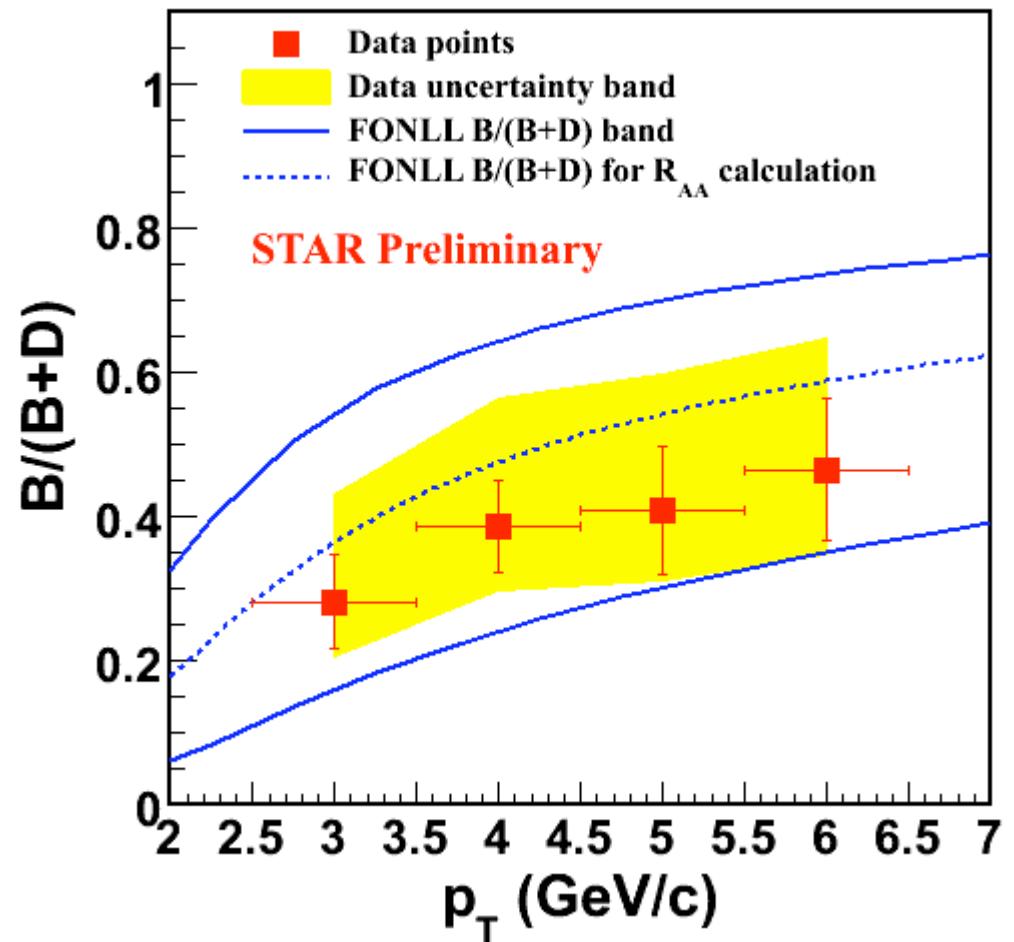


$$\Delta\phi_{\text{exp}} = R \cdot \Delta\phi_B + (1 - R) \cdot \Delta\phi_C$$

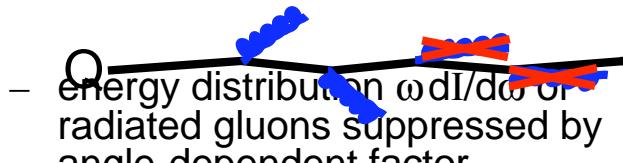
e-h correlations in p+p: bottom vs. charm

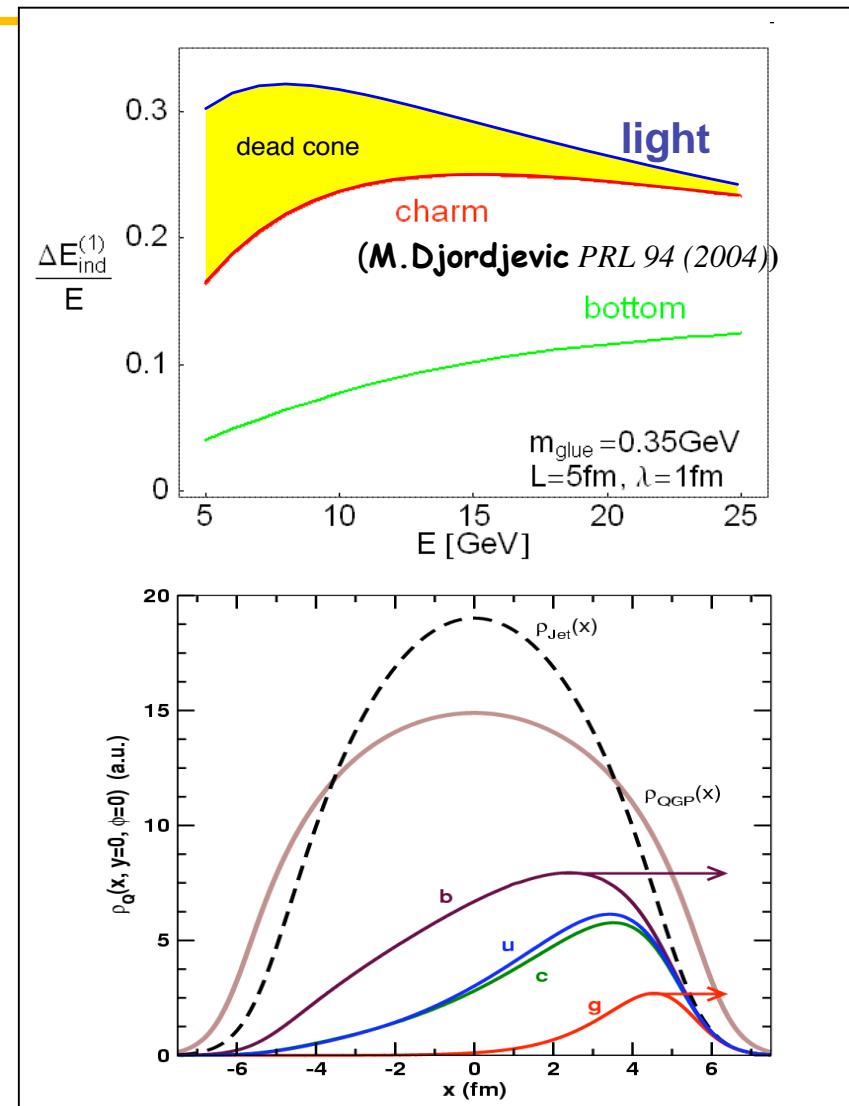
See Xiaoyan Lin's talk for STAR

- FONLL has large uncertainties in the b/(c+b) ratio
 - Could the data nail it down?
- First measurement of open-bottom at RHIC
 - **Non-zero contribution of bottom**
 - **Very close to FONLL predictions**



Open Heavy Flavors – Energy Loss in Medium

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
 - “dead cone” effect implies lower energy loss (Dokshitzer-Kharzeev, ‘01)
-  energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
- Smaller energy loss would probe inside the medium
- Collisional E-loss: $qg \rightarrow qg$, $qq \rightarrow qq$
 - $dE/dx \propto \ln p$ - small?



Nuclear Shadowing

$$F_T(x, Q^2) = \frac{1}{2} \sum_f Q_f^2 \int d\lambda_0 e^{ix\lambda_0} \left\langle p \left| \bar{\Psi}(0) \frac{\gamma^+}{2p^+} \Psi(\lambda_0) \right| p \right\rangle$$

$$= \frac{1}{2} \sum_f Q_f^2 \phi_f(x, Q^2) + O(\alpha_s)$$

$$x_B = \frac{Q^2}{2m_N v}$$

- Simplistic view: modification of the nuclear wave function

Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ then $\Delta z > r_0$

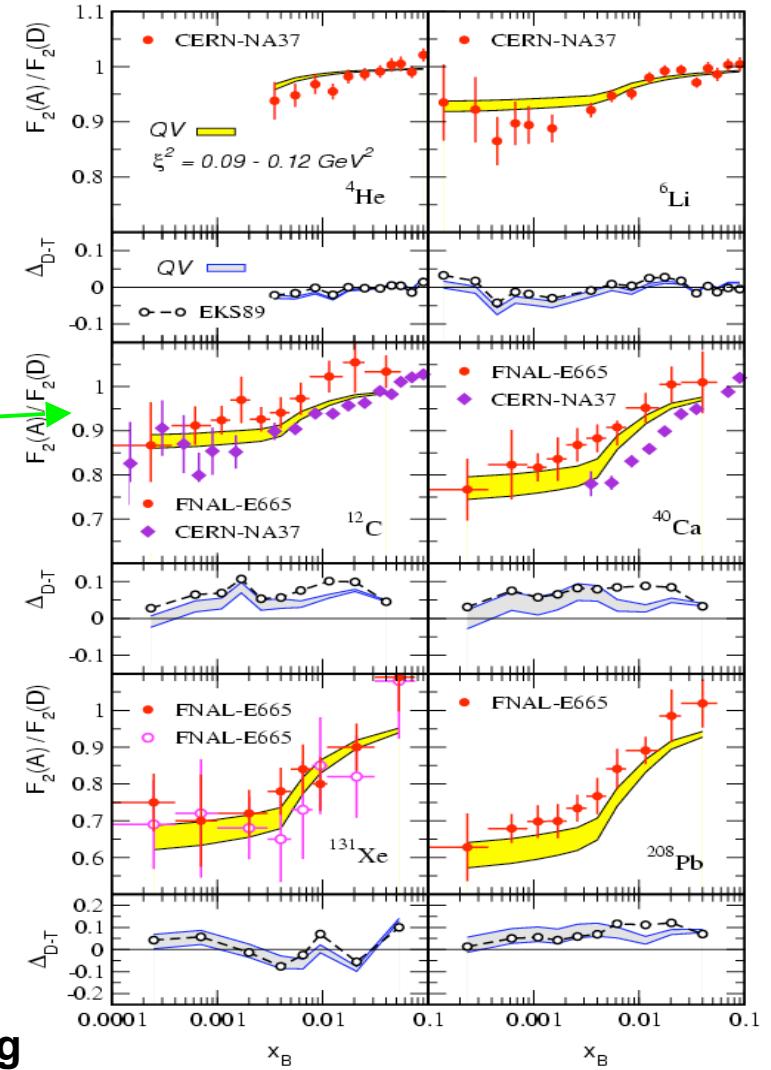
$$F_T^A(x, Q^2) \approx A F_T^{(LT)} \left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2 \right) = A F_T^{(LT)} \left(x \left(1 + \frac{m_{dyn}^2}{Q^2} \right), Q^2 \right)$$

Alternative model: “leading twist” $\sim \ln Q^2$

S.Brodsky et al, Phys.Rev.D65 (2002)

- Shadowing is dynamically generated in the hadronic collision by coherent final state scattering

Deviation from A-scaling: $\sigma_A \neq A \times \sigma$



J.W.Qiu, I.V., Phys.Rev.Lett. 93 (2004)

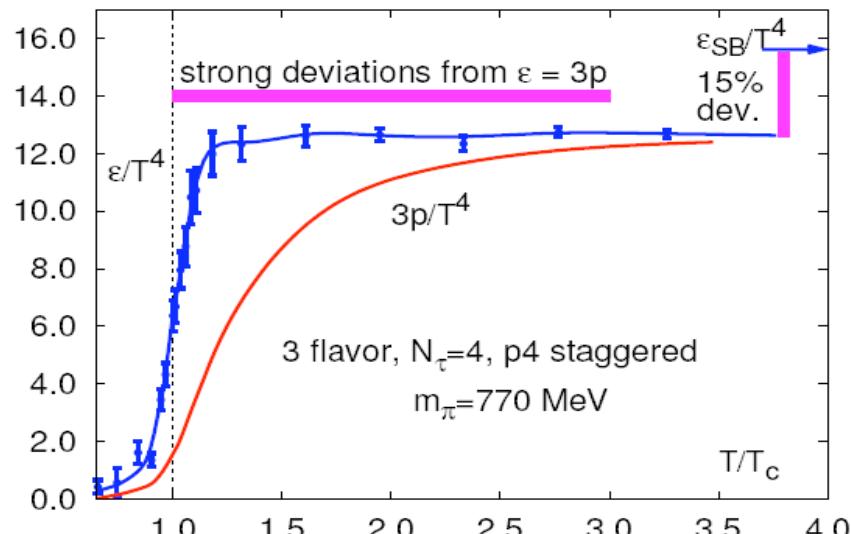
The QCD Phase Transition

Asymptotic freedom:

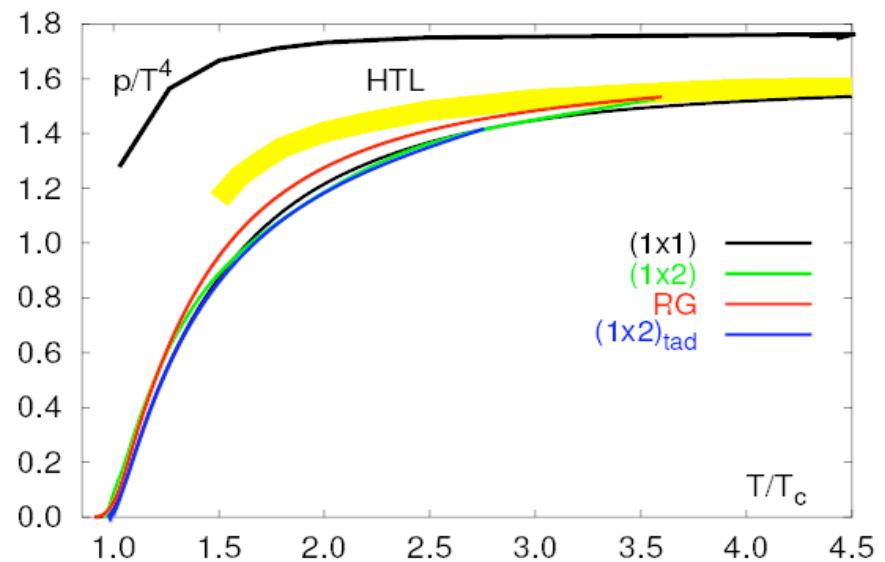
$$T \gg gT \gg g^2 T$$

$$\alpha_s^{LO}(Q^2, n_f) = 4\pi / \left(11 - \frac{2}{3}n_f \right) \ln \frac{Q^2}{\Lambda_{QCD}^2}$$

$$\alpha_s(Q^2, n_f) = \alpha_s^{LO}(Q^2, n_f) \left[1 - \frac{1}{4\pi} \frac{102 - \frac{38}{3}n_f}{11 - \frac{2}{3}n_f} \alpha_s^{LO}(Q^2, n_f) \ln \ln \frac{Q^2}{\Lambda_{QCD}^2} \right]$$



F.Karsch,E.Laermann,A.Peikert, Phys.Lett.B487, (2000)



J.P.Blaizot,E.Iancu,A.Rebhan, Phys.Lett.B470, (1999)

- Deviation from Stefan-Boltzman: the log running of α_s



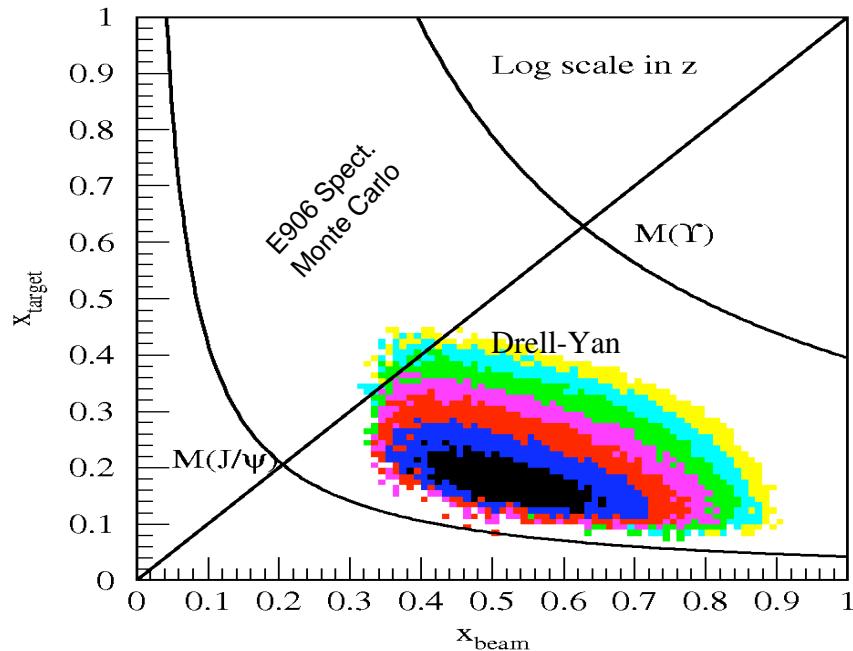
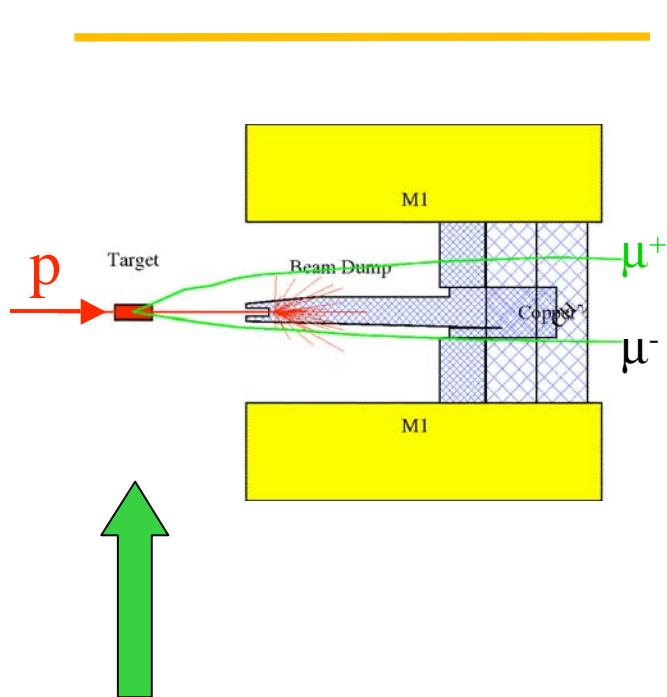
Note: recent results $T_c \sim 190$ MeV vs $T_c \sim 175$ MeV

Note on LHC versus RHIC: strongly versus weakly coupled plasmas, beware of logarithmic running

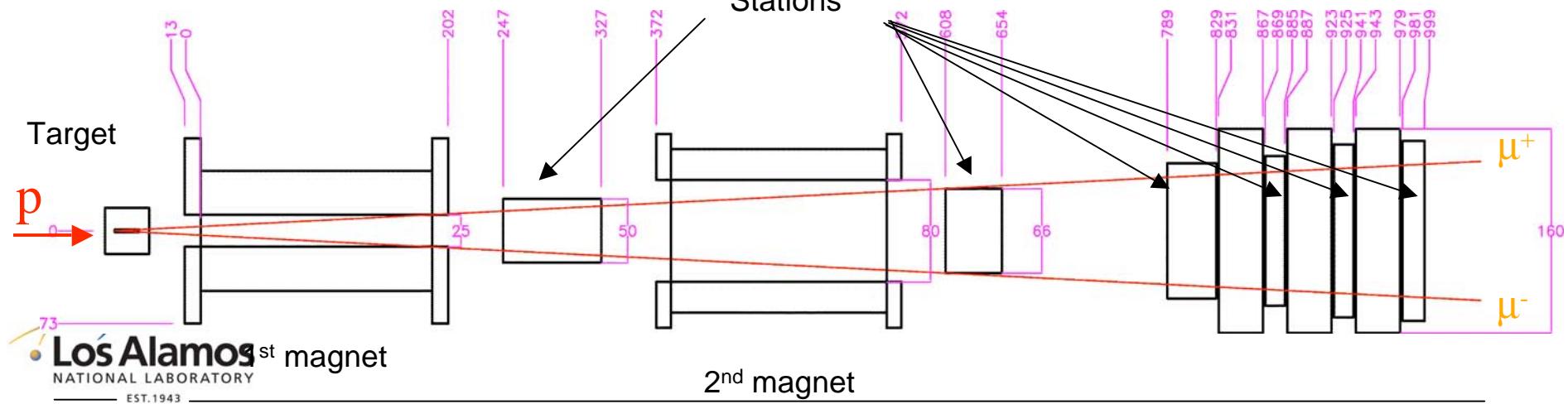
- Hard thermal loop calculations: improved resummation of the perturbation series
- Agreement between HTL and Lattice for $T \geq 3T_c$

The E906 Experiment at Fermilab

38



Beam energy
of 120 GeV
eliminates
shadowing
region



Ivan Vitev

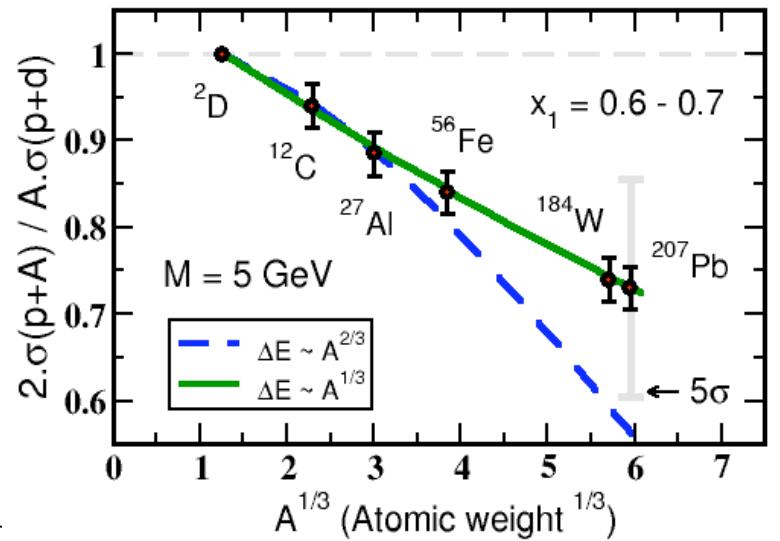
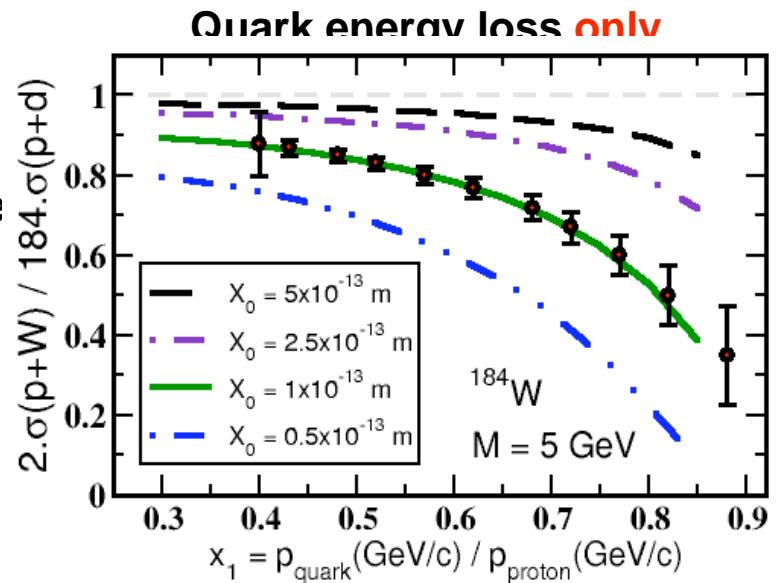
- For radiation lengths $X_0 = 1 \times 10^{-13}$ m achieve sensitivity $\sim 20\%$

Non-QCD $X_0(W) = 3.5 \times 10^{-3}$ m

- Clearly distinguish between leading models for dependence of E-loss (5σ)

$$-\Delta E \sim A^{1/3} \text{ (or } \sim L)$$

$$-\Delta E \sim A^{2/3} \text{ (or } \sim L^2)$$



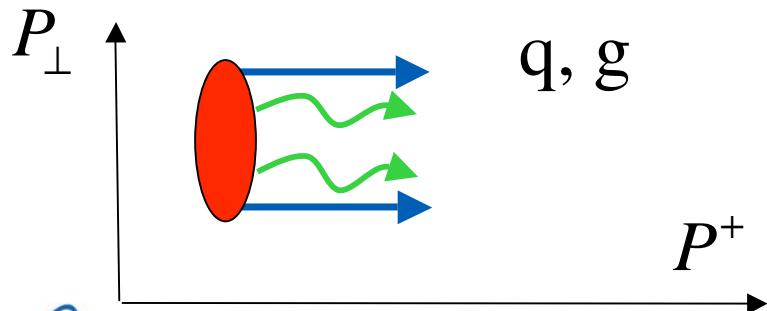
Light Cone Wave Functions

- Expansion in Fock components

$$\left| \psi_M; P_\perp, P^+ \right\rangle = \sum_{i=2}^n \int \frac{dx_i}{\sqrt{2x_i}} \frac{d^2 k_{\perp i}}{\sqrt{(2\pi)^3}} \psi_i(k_{\perp i}, x_i) \\ \times \delta\left(\sum_{i=2}^n x_i - 1\right) \delta\left(\sum_{i=2}^n k_{\perp i}\right) \left| i; k_{\perp i} + x_i P_\perp, x_i P^+ \right\rangle$$

S.Brodsky, D.S.Hwang, B.Q.Ma, I.Schmidt, Nucl.Phys.B 592 (2001)

Fix two momentum scales



- Fixing the transverse momentum scale

Cornell potential $V(r) = -\frac{\xi}{r} + br$

$$\left[\alpha \cdot p + V + (m + S)\beta + \frac{p^2}{2M_Q} + \left\{ \frac{\alpha \cdot p}{2M_Q}, V \right\} \right. \\ \left. + \frac{1}{4M_Q} [\alpha \cdot p, [p^2, W]] \right] \psi = E \psi$$

$$a_0 \rightarrow \max(r^2 \rho(r)), \quad a_0 = 2-3 \text{ GeV}^{-1}$$

M. Avila, Phys.Rev.D49 (1994)

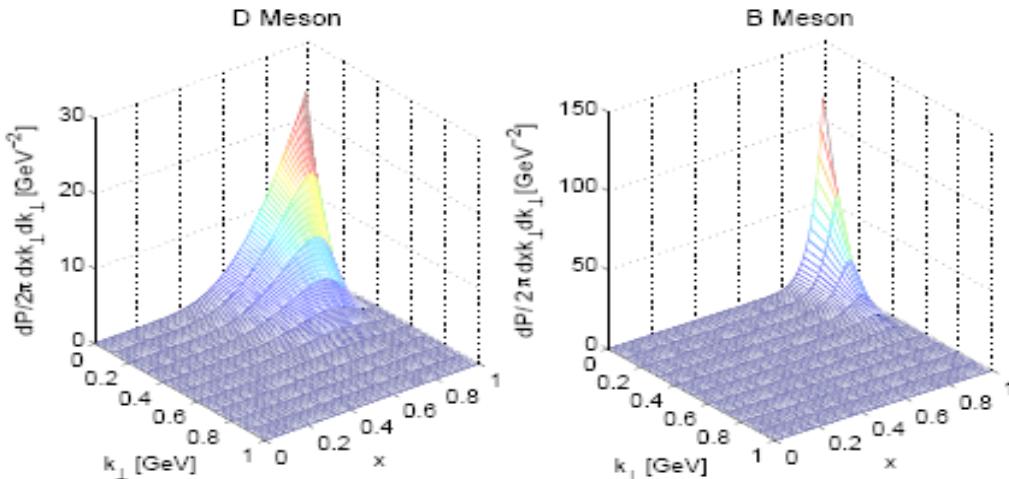
Fourier transform to momentum space

$$\psi(r) \sim e^{r^2/(2a_0^2)} \rightarrow \psi(k) \sim e^{k^2 a_0^2 / 2}$$

Typical transverse momentum squared $\langle k_\perp^2 \rangle = \frac{1}{2a_0^2}$

Light Cone Wave Functions

- Results for heavy flavor



- Fixing the longitudinal momentum fractions

$$\left(\frac{m_{\perp i}^2}{x_i} = \frac{m_i^2 + k_{\perp i}^2}{x_i} \right) = \left(\frac{m_{\perp j}^2}{x_j} = \frac{m_j^2 + k_{\perp j}^2}{x_j} \right)$$

Meson boost – equal quark longitudinal rapidity

- Begin to understand hadron structure and parton distributions from first principles

$$\phi_{Q/M}(x) = \int dK d^2 \Delta k_{\perp} \left| \psi(K, \Delta k_{\perp}, x, m_1, m_2) \right|^2$$

- Duality between FFs ad PDFs

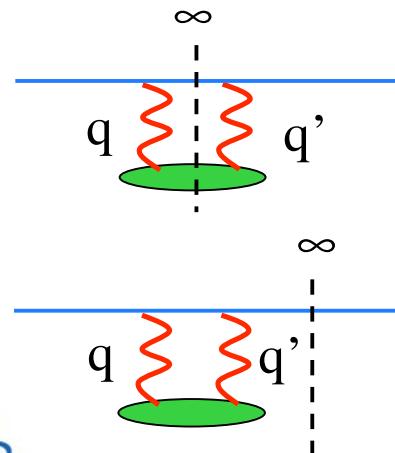
- Models such as coalescence should use plausible wave functions, especially for heavy flavor

From general theory of LCWF for the **lowest-lying Fock state**

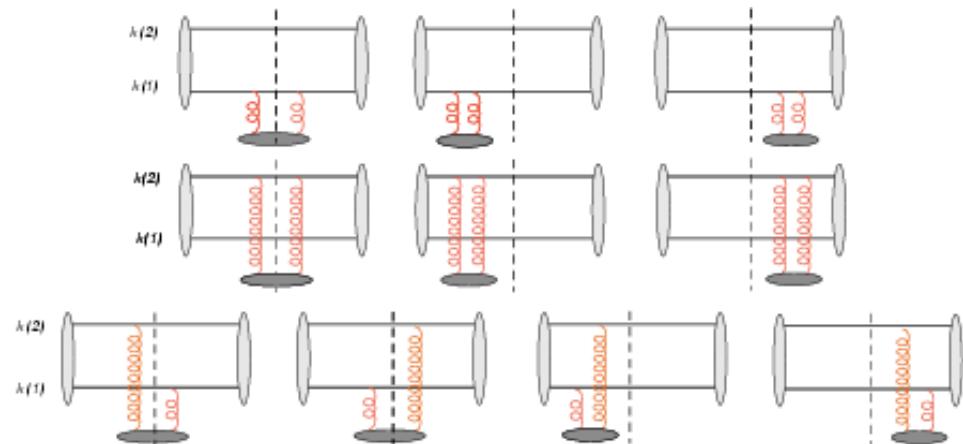
Heavy Meson Propagation in Dense Matter

$$R = \left(\begin{array}{c} \text{Diagram of a quark-gluon loop in a medium} \\ \text{with boundary conditions } 1/\mu \ll \lambda \end{array} \right) n$$

- Solve for the color and kinematic structure of this **operator** which automatically ensures unitarity



- Single scattering in the medium



$$\sim \int d^2 q_\perp d^2 q'_\perp M_1^*(p - q_\perp) M_2(p - q'_\perp) \frac{d\sigma_{el}}{d^2 q_\perp} \delta^2(q_\perp - q'_\perp)$$

$$\sim \left(-\frac{1}{2} \right) \int d^2 q_\perp d^2 q'_\perp M_1^*(p - q_\perp - q'_\perp) M_2(p) \frac{d\sigma_{el}}{d^2 q_\perp} \delta^2(q_\perp + q'_\perp)$$

Medium-Modified Heavy Meson

Initial distribution:

$$|\psi_i(\Delta k_\perp, x)|^2 = [\delta^2(K_\perp)] \times \left[\text{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}} e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}} \right]$$

Resum multiple scattering in impact parameter (B,b) space

- Heavy meson acoplanarity: $\langle K_\perp^2 \rangle = 2 \left(2\mu^2 \frac{L}{\lambda_q} \xi \right) - 2 \left(2\mu^2 \frac{L}{\lambda_q} \xi \right) \equiv \int_0^L 2 \left(2\mu^2(l) \frac{1}{\lambda_q(l)} \xi \right) dl$

$$|\psi_f(\Delta k_\perp, x)|^2 = \left[\frac{e^{-\frac{K_\perp^2}{4\chi\mu^2\xi}}}{4\chi\mu^2\xi} \right] \times \left[\text{Norm}^2 \frac{x(1-x)\Lambda^2}{\chi\mu^2\xi + x(1-x)\Lambda^2} e^{-\frac{\Delta k_\perp^2}{4(\chi\mu^2\xi+x(1-x)\Lambda^2)}} e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}} \right]$$



- Broadening (separation) the q q-bar pair:

$$\psi_f(\Delta k_\perp, x) = a\psi_M(\Delta k_\perp, x) + (1-a)\psi_{q\bar{q} \text{ dissociated}}(\Delta k_\perp, x)$$

Dissociation Rate and Rate Equations

- Distortion of the light cone wave function leads to meson decay

Meson survival probability:

$$P_{\text{surv.}} \left(\frac{\mu^2}{\lambda} L \xi \right) = \left| \int dx d^2 \Delta k_\perp \psi^*_f(x, \Delta k_\perp) \psi_i(x, \Delta k_\perp) \right|^2$$

Dissociation time:

$$\langle \tau_{\text{diss}} \rangle = \frac{d}{dt} \ln \left(1 - P_{\text{surv.}} \left(\frac{\mu^2}{\lambda_q} L(t) \xi \right) \right)$$

$$\begin{aligned} \partial_t f^Q(p_T, t) &= -\frac{1}{\langle \tau_{\text{form}}(p_T, t) \rangle} f^Q(p_T, t) \\ &\quad + \frac{1}{\langle \tau_{\text{diss}}(p_T / \bar{x}, t) \rangle} \int_0^1 dx \frac{1}{x^2} \phi_{Q/H}(x) f^H(p_T / x, t) \\ \partial_t f^H(p_T, t) &= -\frac{1}{\langle \tau_{\text{diss}}(p_T, t) \rangle} f^H(p_T, t) \\ &\quad + \frac{1}{\langle \tau_{\text{form}}(p_T / \bar{z}, t) \rangle} \int_0^1 dz \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T / z, t) \end{aligned}$$

Solve with the initial conditions

$$f^Q(p_T, t) = \frac{d\sigma^Q(p_T, t)}{dy d^2 p_T}, \quad f^H(p_T, t) = \frac{d\sigma^H(p_T, t)}{dy d^2 p_T}$$

$$f^Q(p_T, t=0) = \frac{d\sigma^Q_{\text{PQCD}}}{dy d^2 p_T}, \quad f^H(p_T, t=0) \equiv 0$$

Find the asymptotic solutions

$$t \gg \max(L_{QGP}, \tau_{\text{form}})$$

Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i} \left(p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ij}(p,t) \right) \partial f(p,t)$$

- Drag coefficient:

$$A_i(p,t) = \frac{1}{p_i} \frac{\langle \delta p_i \rangle}{\delta t}$$

[Fractional momentum loss per unit time]

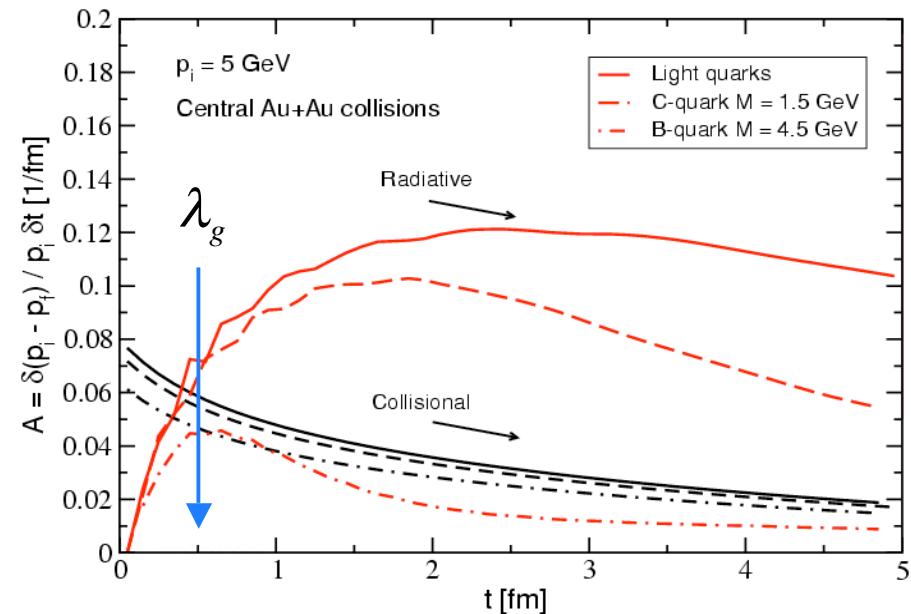
- Diffusion coefficient:

$$B_{ji}(p,t) = \frac{1}{2} \frac{\langle \delta p_j \delta p_i \rangle}{\delta t}$$

Equilibration is imposed by Einstein's fluctuation-dissipation relation:

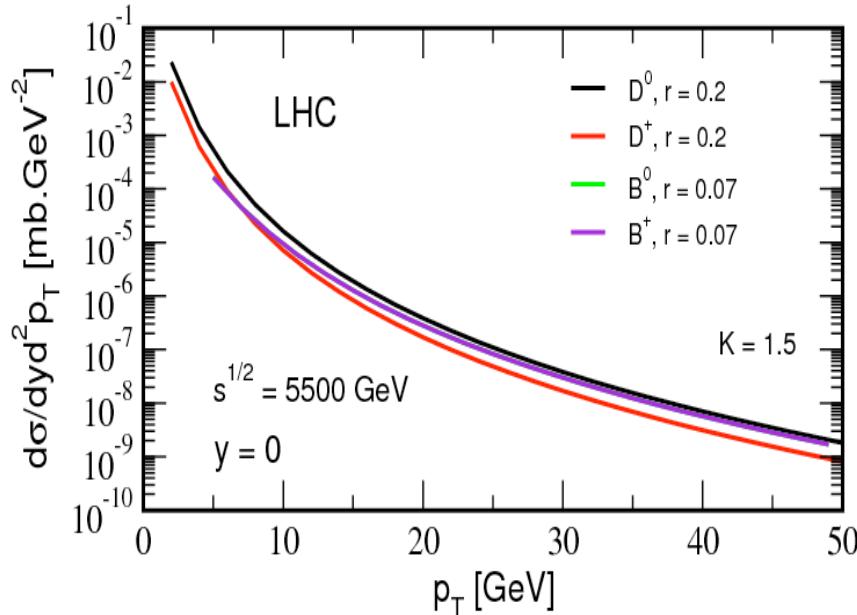
$$B_{||}(p,t) = T(t) E(p) A_i(p,t)$$

H. van Hees, I. Vitev, [R. Rapp], in preparation



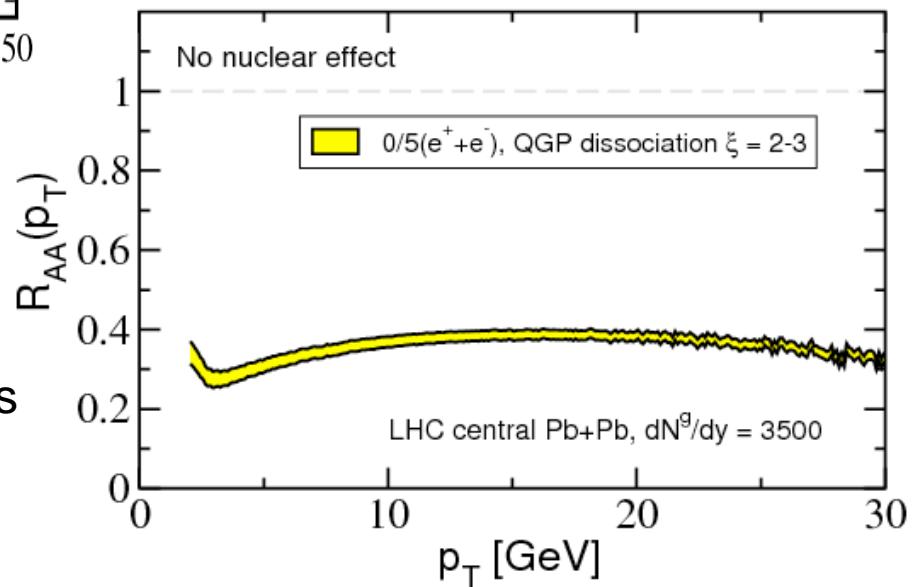
- Radiative energy loss is dominant except for b-quarks and very small systems

Situation at the LHC



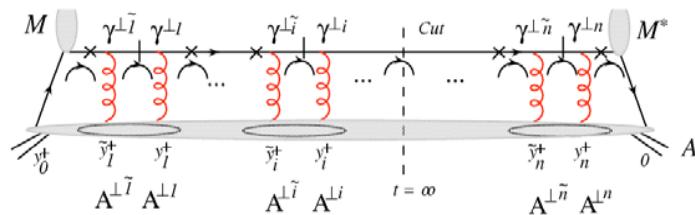
- Harder spectra at the LHC
- Electrons spectra from B-mesons and D-mesons decays contribute cross at higher p_T

- The asymptotic solution in the QGP - sensitive to $t_0 \sim 0.6$ fm and expansion dynamics
- Features of energy loss
- Suppression at the LHC not different when compared to RHIC



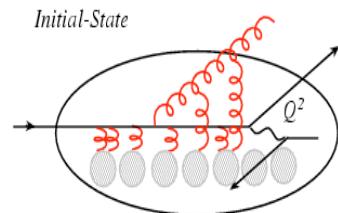
Critical Future Directions

- Dynamical nuclear shadowing



J.W. Qiu, I.V., Phys. Lett. B 632 (2006)

- Dynamical nuclear shadowing



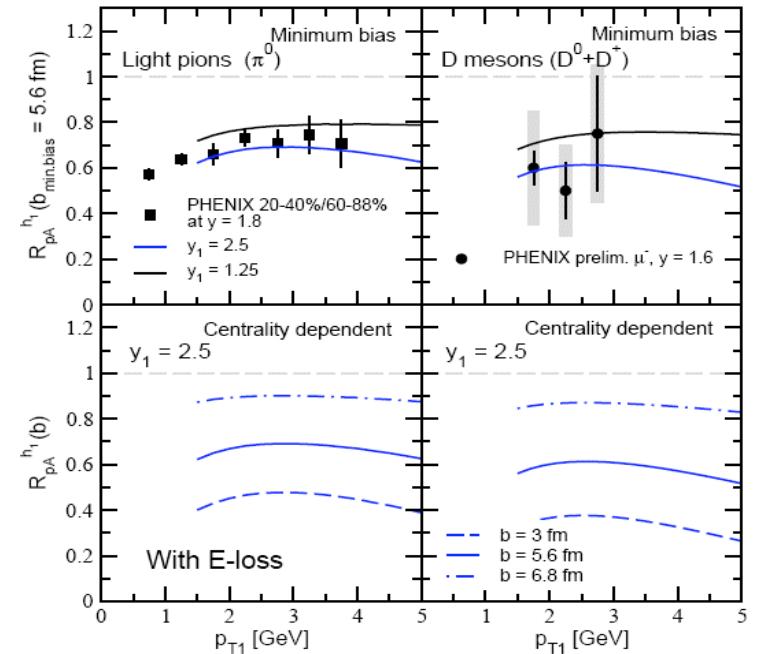
$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \times \ln \frac{Q_0}{\mu}$$

I.V., Phys. Rev. C (2007), hep-ph/0703002

Carry systematic calculations in A+A at forward rapidity

Experimental $y = 1.4\text{-}2.2$

Very similar behavior of charm quarks (D-mesons) to light hadrons

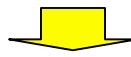


I.V., T.Goldman, M.Johnson, J.W.Qiu, Phys. Rev. D 74 (2006)

Experimental Tools for Heavy Mesons

- Vertex detectors at midrapidity
- Vertex detectors at forward rapidity

Experimentally validate / disprove theories

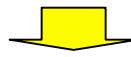


Collisional
dissociation

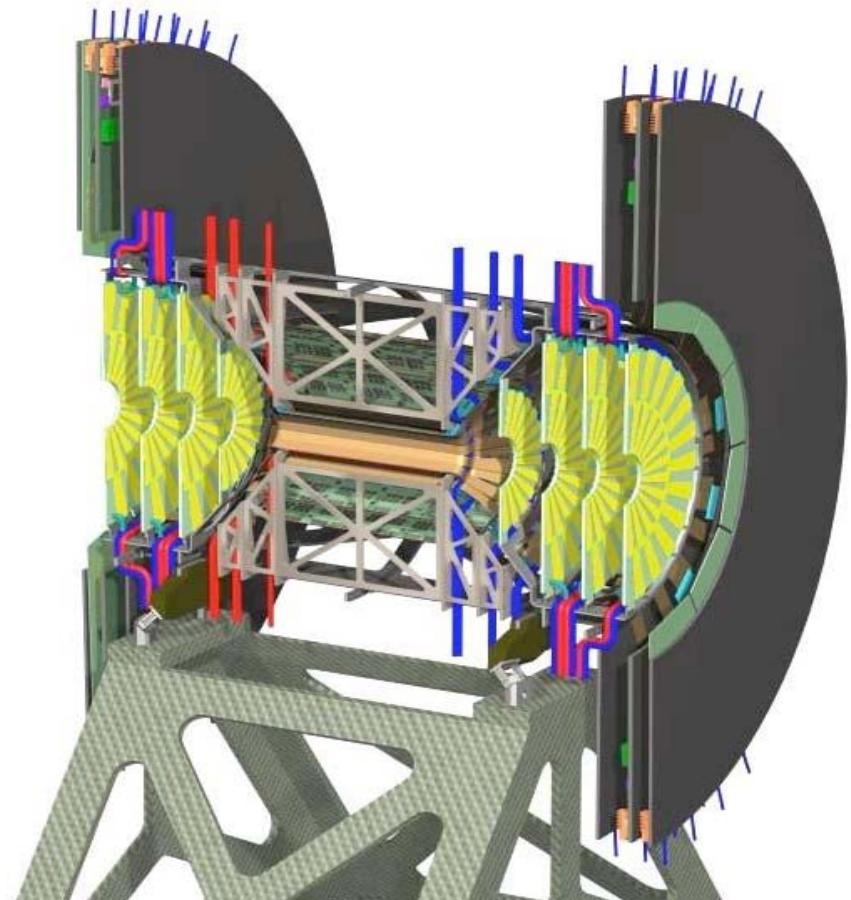
Mainstream
approach

$$R_{AA}(p_T; \textcolor{blue}{B}) \approx R_{AA}(p_T; \textcolor{blue}{D})$$

$$R_{AA}(p_T; \textcolor{blue}{B}) \gg R_{AA}(p_T; \textcolor{blue}{D})$$



- Best reason to measure D- and B-mesons **separately**



Summary of Open Heavy Flavor Modification

Cold nuclear matter effects on open heavy flavor

- Determined the baseline heavy flavor production in p+p collisions
- Calculated dynamical shadowing from coherent final state interactions
- Progress in understanding cold nuclear matter initial state energy loss

Collisional QGP-induced B- / D-meson dissociation

- Derived formation and dissociation times in the QGP. They are short
- Improved description of non-photonic electron quenching
- B-mesons are as suppressed as D-mesons at $p_T \sim 10$ GeV, unique

Langevin simulation of heavy quark diffusion

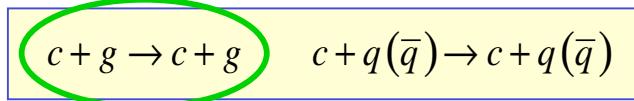
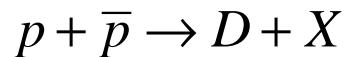
- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

Future directions

- Combine cold nuclear matter effects with the QGP suppression models to predict the open heavy flavor modification at forward rapidity

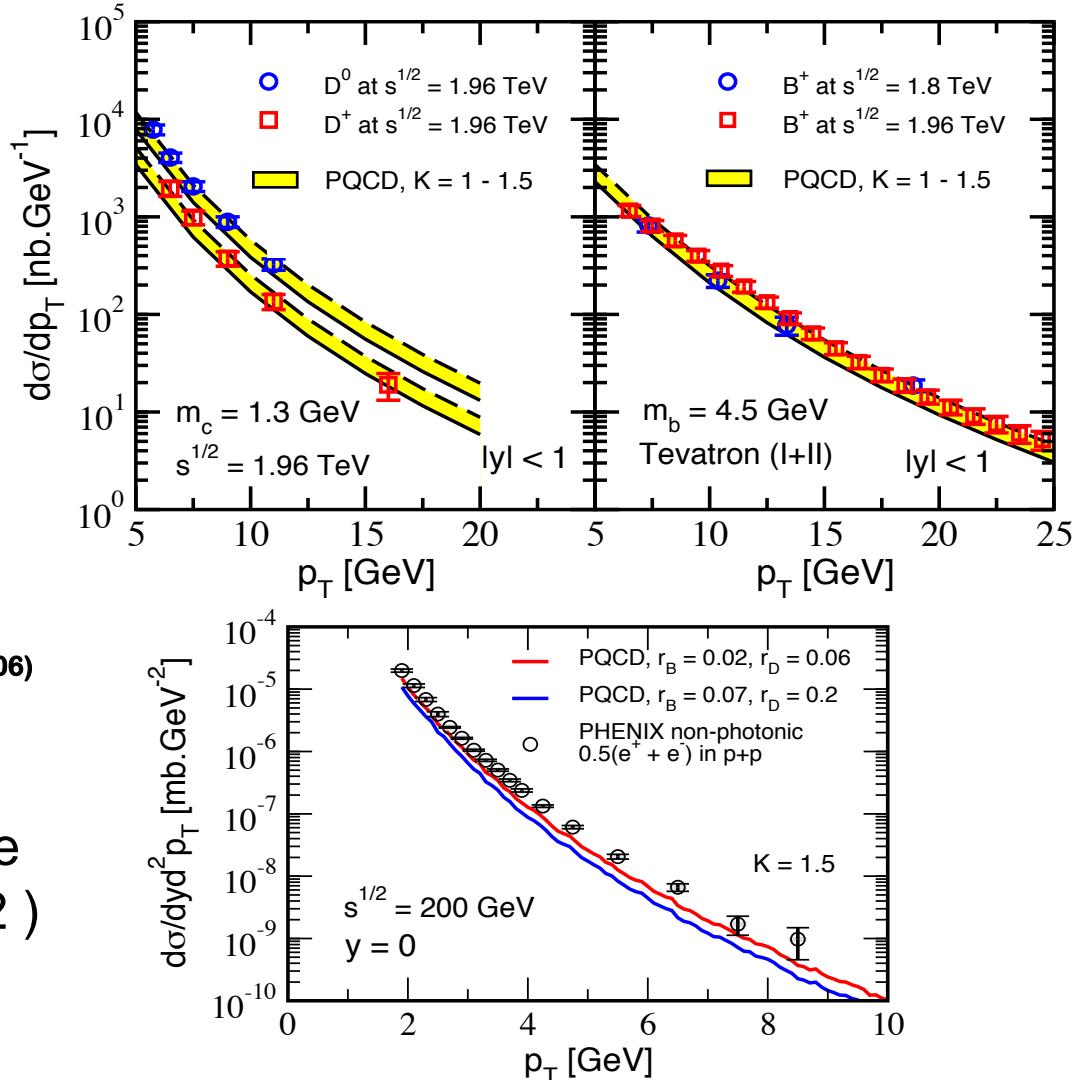
Heavy Quark Production in p+p Collisions

- Gluon fusion is **not** the dominant hard process in **single inclusive** open charm (bottom) production



I.V., T.Goldman, M.Johnson, J.W.Qiu, Phys.Rev.D74 (2006)

- Comparable to “NLO” results: (under-predicts the cross section by 30% - x 2)



Perturbative Expansion for Heavy Mesons

Single inclusive D - mesons

$$d\sigma^{(1)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2)$$

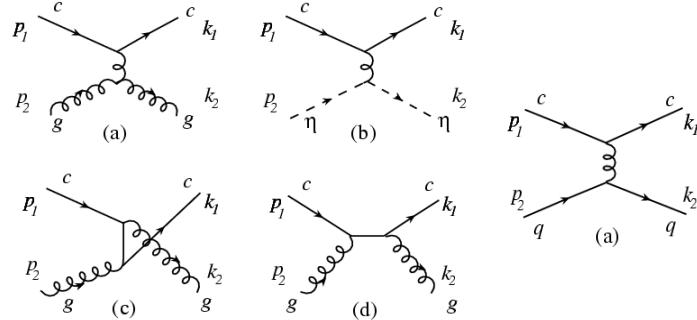
$$\otimes \frac{1}{2\hat{s}} |M|^2 \otimes D_1(z_1, Q^2)$$

D - meson triggered back-to-back correlations

$$d\sigma^{(2)} \sim \phi_1(x_1, Q^2) \otimes \phi_2(x_2, Q^2)$$

$$\otimes \frac{1}{2\hat{s}} |M|^2 \otimes D_1(z_1, Q^2) \otimes D_2(z_2, Q^2)$$

Flavor excitation

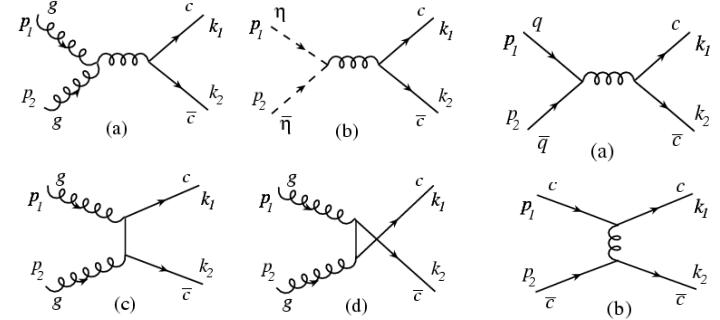


Faster convergence of the perturbative series

Two different expansions

F. Olness et al., Phys. Rev. D59 (1999)

Flavor creation



Slower convergence of the perturbative series

- Advantages: much faster convergence in α_s^n of the hard scatter $|M|^2$

Fragmentation Probability for Heavy Quarks

Recall: $\Delta y^+(z, m_h, M_Q, p^+) = \frac{1}{\Delta p^-} = \frac{(0.2 \text{ GeV.fm}) 2z(1-z) p^+}{k_\perp^2 + (1-z)m_h^2 - z(1-z)M_q^2}$

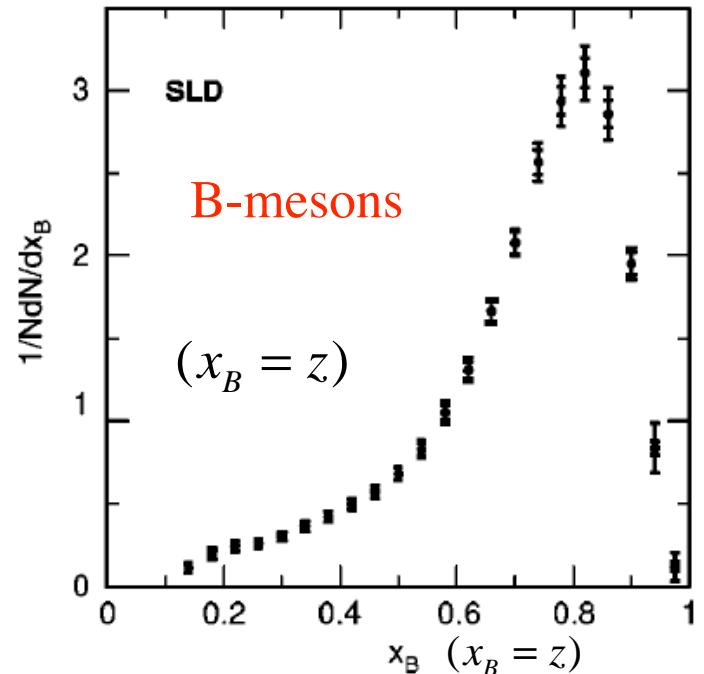
$$\tau_{\text{form}}(z, m_h, M_Q, p^+) = \Delta y^+ / (1 + \beta_Q)$$

- Fragmentation probability

$$\int_0^1 D_{D_i, B_i/c, b}(z, Q^2) dz = f_i(D_i, B_i/c, b)$$

$$\sum_{i=1}^n f_i(B/b; D/c) = 1 \quad \text{Universal in the QCD factorization approach}$$

$$\langle \tau_{\text{form}} \rangle = \sum_i \int_0^1 \tau_{\text{form}}(z, m_{hi}, M_Q, p^+) D_{h_i/Q}(z, Q^2) dz$$



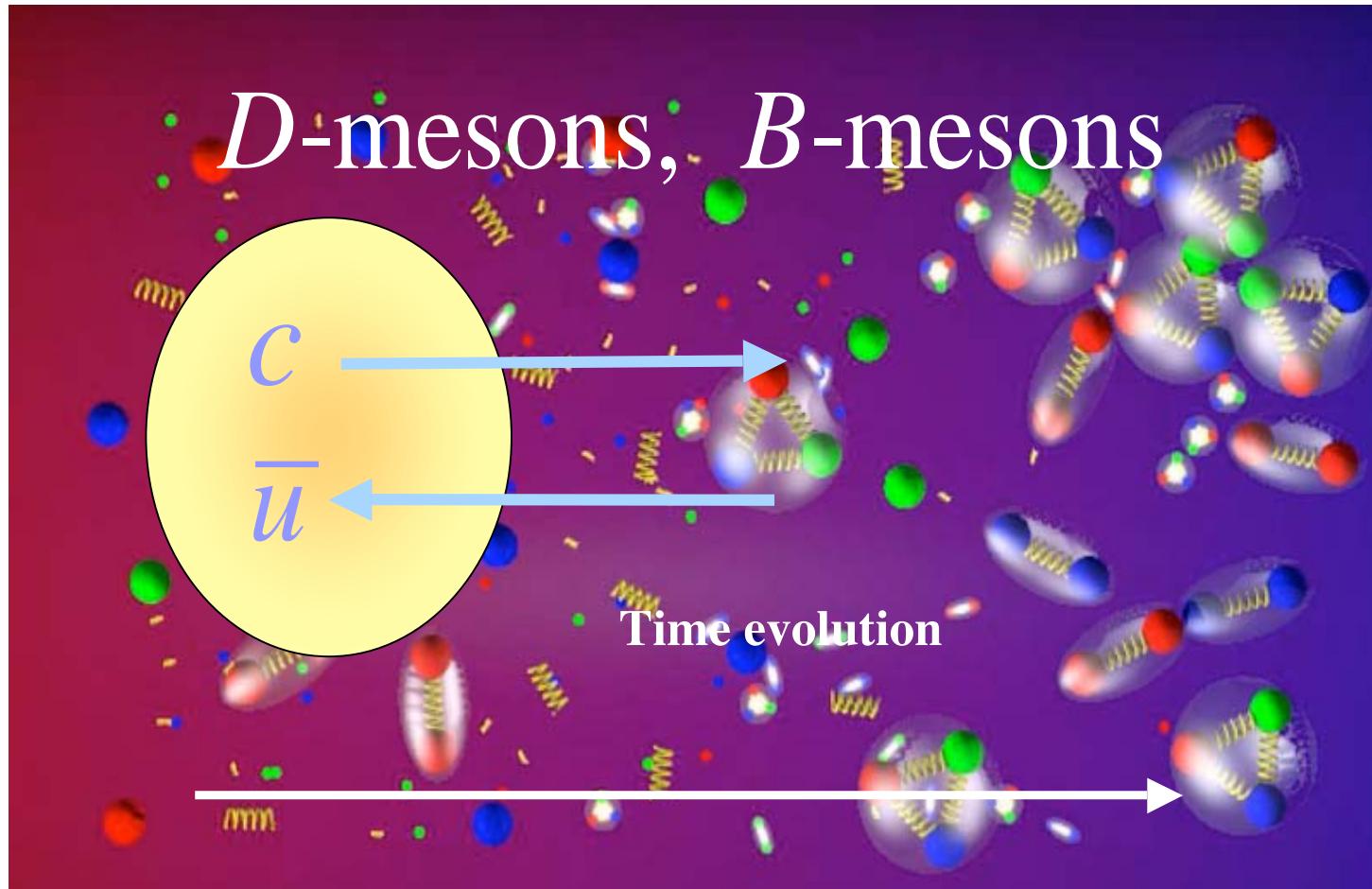
FFs from heavy quark EFT

K.Cheung,T.Z.Yuan, Phys.Rev.D53 (1996)

- Time-dependent implementation

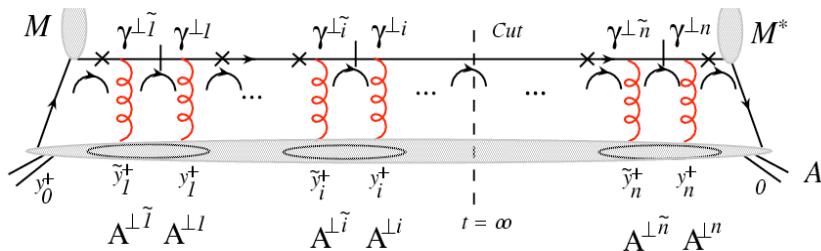
$$N_Q(t) = N_Q(0) \exp \left[-\frac{t}{\langle \tau_{\text{form}} \rangle} \right]$$

A New Paradigm

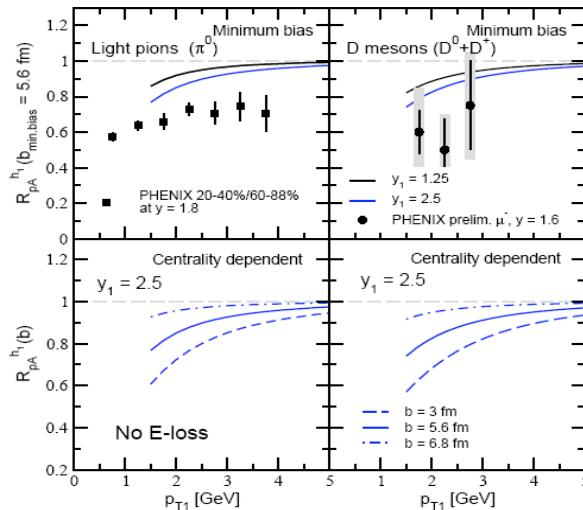


Cold Nuclear Matter Effects in PQCD

- Shadowing arises from coherent final-state multiple scattering

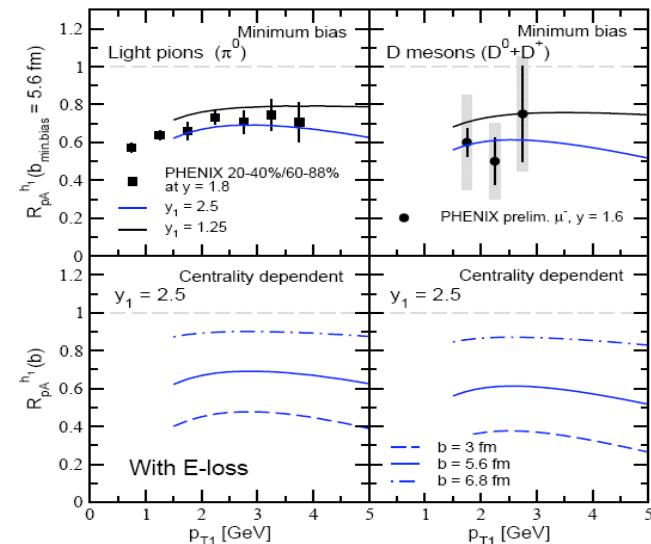


$$F(x_b) = \frac{\phi(x_b)}{x_b} \left| \bar{M}_{ab\leftrightarrow cd}^2 \right|, \quad F(x_b) \rightarrow F \left(x_b + x_b C_d \frac{\xi^2}{-t + m_d^2} (A^{1/3} - 1) \right)$$



- Cold nuclear matter energy loss plays an important role (may be dominant) in p+A

- Experimental $y = 1.4-2.2$



I. Vitev, T.Goldman, M.Johnson, J.W.Qiu, Phys. Rev. D 74 (2006)

Very similar behavior of charm quarks (D-mesons) to light hadrons

Strategy for Calculating HF Suppression

- Calculate the baseline D- and B-meson cross sections in p+p collisions
- Calculate the fragmentation probability of heavy quarks
- Calculate the QGP-induced dissociation probability for heavy mesons
- Solve the system of coupled rate equations and predict the heavy quark (single electron) suppression

Detailed Analysis to LO

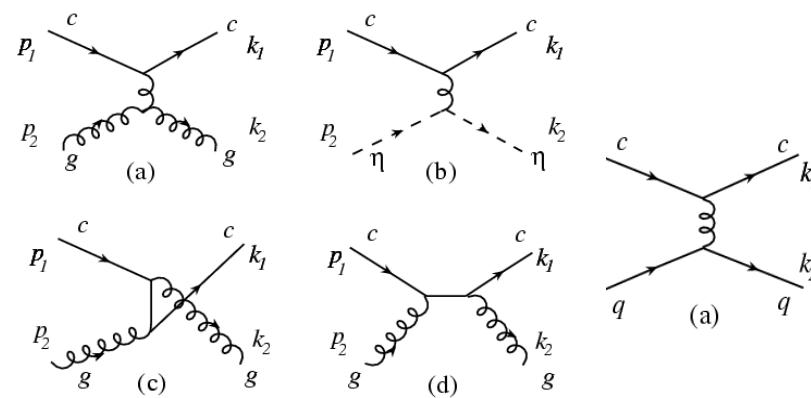
Single inclusive D - mesons

$$\frac{d\sigma_{NN}^{D_1}}{dy_1 d^2 p_{T_1}} = K_{NLO} \sum_{abcd} \int_{x_{1,2} \leq 1} dy_2 \int_{x_{1,2} \leq 1} dz_1 \times \frac{1}{z_1^2} D_{D_1/c}(z_1) \frac{\phi_{a/N}(x_a) \phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab \rightarrow cd}|^2$$

D - meson triggered back-to-back correlations

$$\frac{d\sigma_{NN}^{D_1 h_2}}{dy_1 dy_2 dp_{T_1} dp_{T_2}} = K_{NLO} \sum_{abcd} 2\pi \int_{\mathcal{D}} \frac{dz_1}{z_1} D_{D_1/c}(z_1) D_{h_2/d}(z_2) \times \frac{\phi_{a/N}(x_a) \phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab \rightarrow cd}|^2$$

Flavor excitation

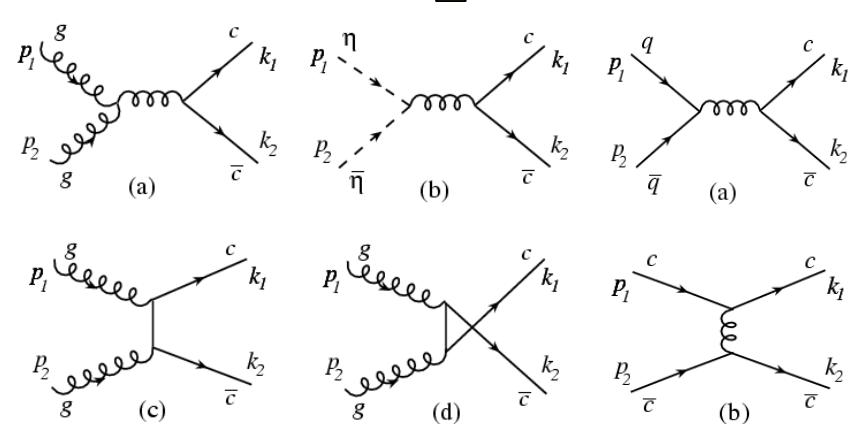


Faster convergence of
the perturbative series

F.Olness et al., Phys.Rev.D59 (1999)

Two different expansions

Flavor creation



Slower convergence of
the perturbative series

Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i} \left(p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ij}(p,t) \right) \partial f(p,t)$$

H. van Hees, I.V., R. Rapp, in preparation

- Drag coefficient:

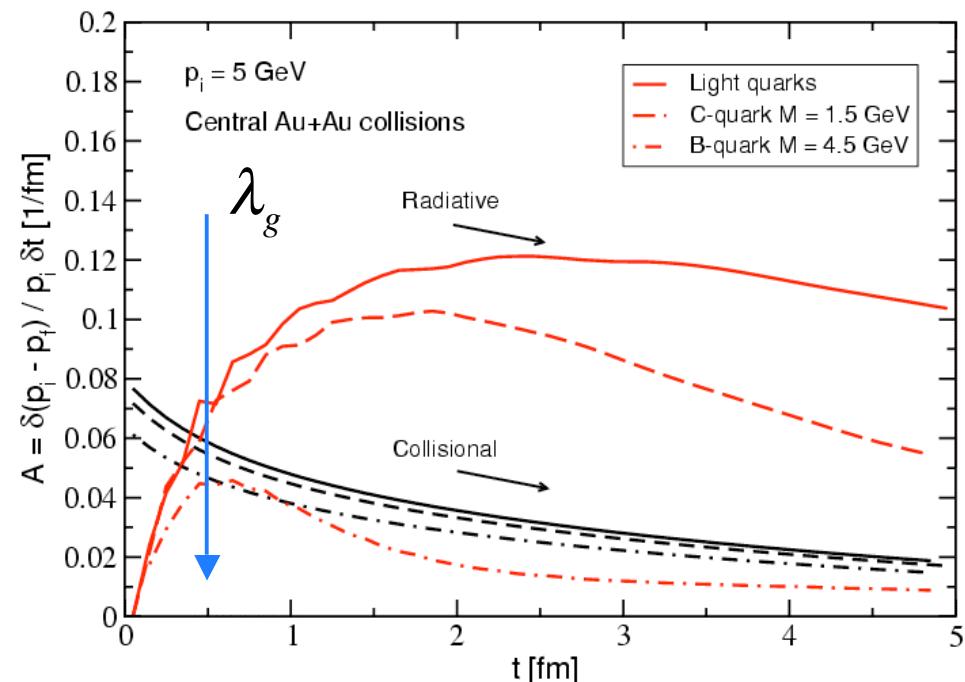
$$A_i(p,t) = \frac{1}{p_i} \frac{\langle \delta p_i \rangle}{\delta t}$$

- Diffusion coefficient:

$$B_{ji}(p,t) = \frac{1}{2} \frac{\langle \delta p_j \delta p_i \rangle}{\delta t}$$

Equilibration is imposed by Einstein's fluctuation-dissipation relation:

$$B_{||}(p,t) = T(t) E(p) A_i(p,t)$$

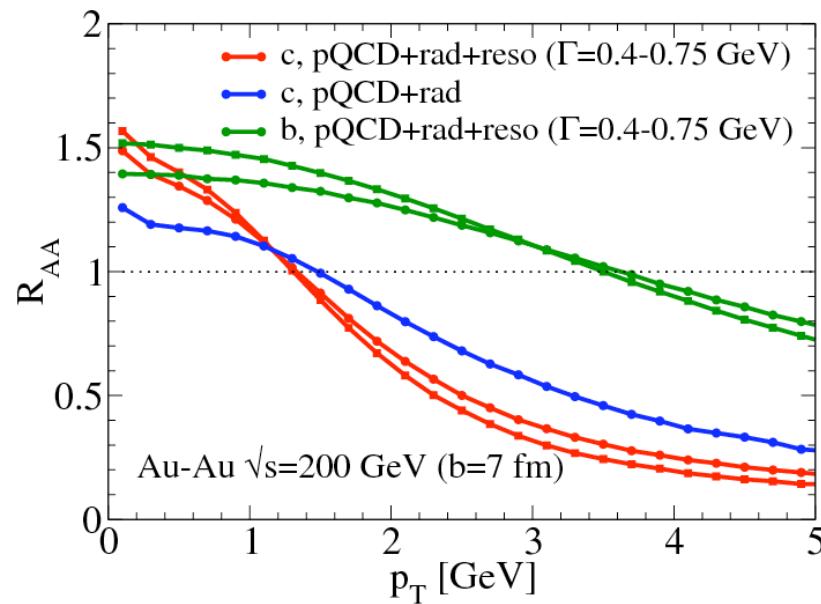


Radiative energy loss is dominant except for b-quarks and very small systems

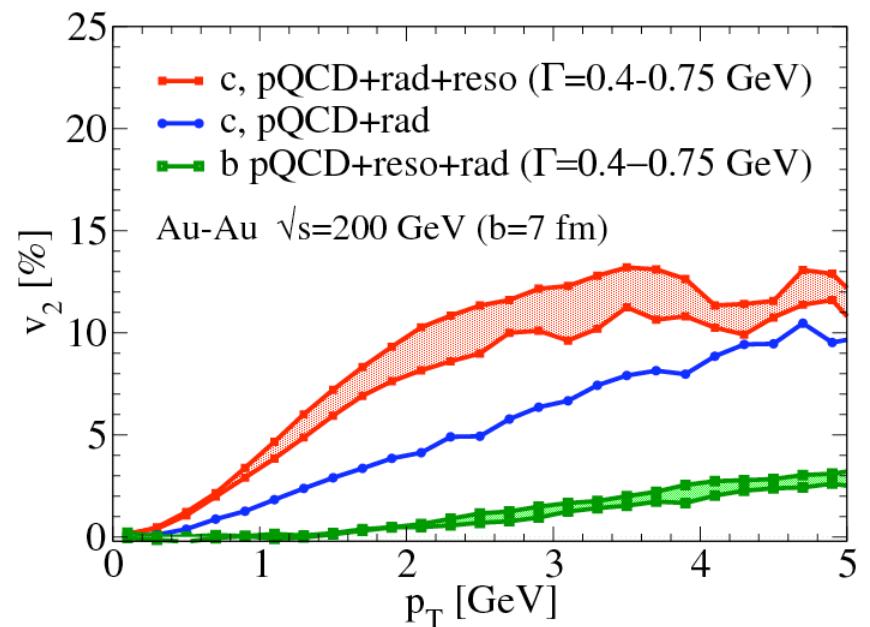
Transport + Quenching Approach

Numerical results for heavy quark diffusion

Results are preliminary



H. van Hees, I.V., R. Rapp, in preparation



- The suppression and v_2 are large when e-loss and q-resonance interactions are combined
- Normal hierarchy: c quarks are significantly more suppressed than b-quarks

Summary of Open Heavy Flavor Modification

Collisional QGP-induced B- / D-meson dissociation

- Derived formation and dissociation times in the QGP. They are short
- Solved the set of coupled rate equations. More sensitive to QGP properties and formation / expansion dynamics than e-loss
- B-mesons are as suppressed as D-mesons at $p_T \sim 10$ GeV, unique

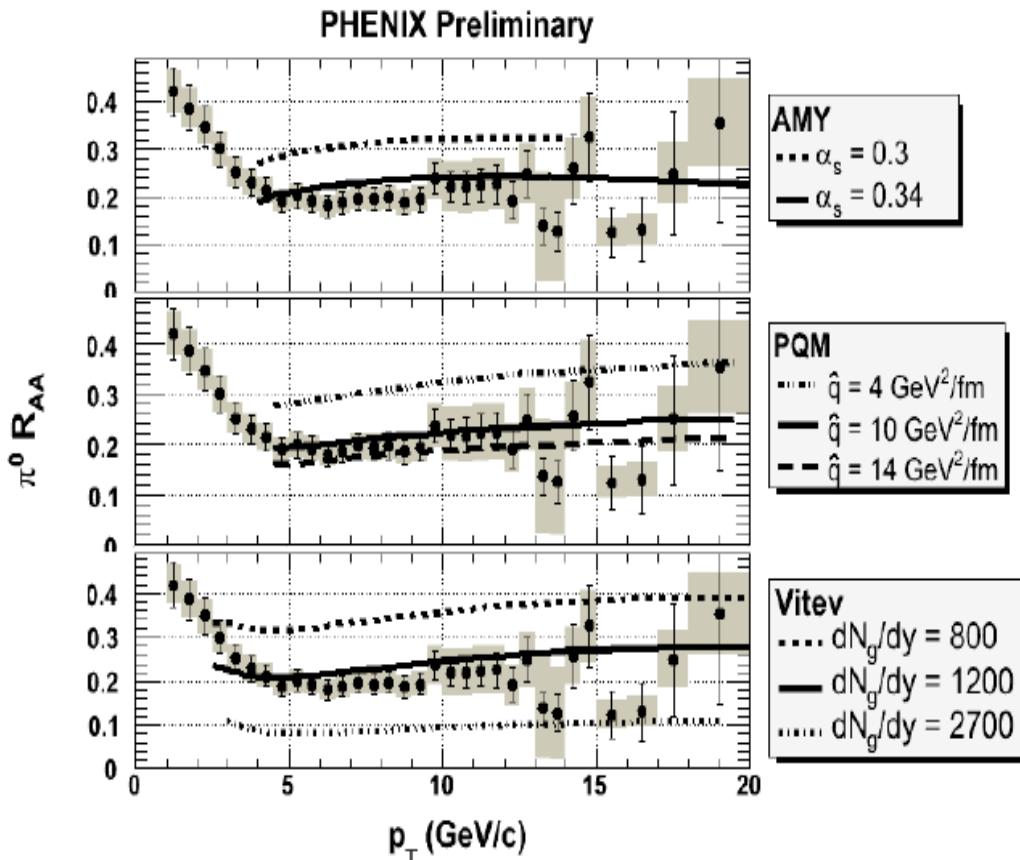
Langevin simulation of heavy quark diffusion

- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

Cold nuclear matter effects on open heavy flavor

- Calculated dynamical shadowing from coherent final state interactions
- Calculated the cold nuclear matter initial state energy loss
- Combine with the QGP suppression to make predictions at forward rapidity

Comparison to Other Models



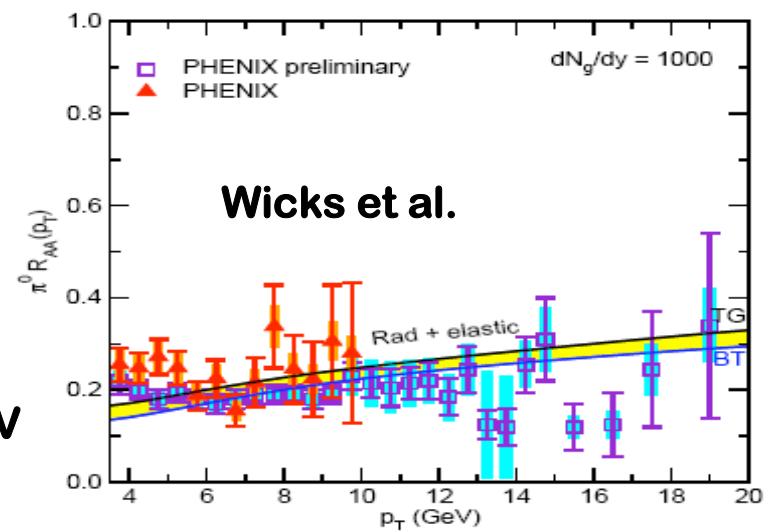
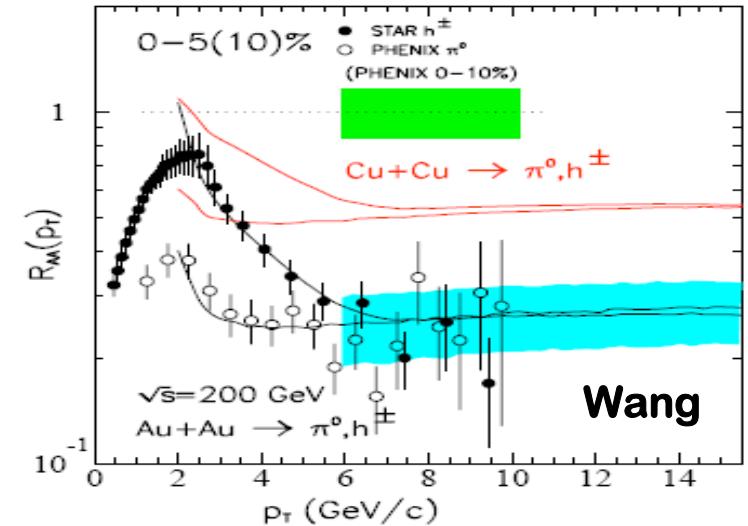
**How do you build
from $T = 400 \text{ MeV}$**

$$\hat{q} = \frac{\mu^2}{\lambda_g} = 100 \text{ GeV}^2 / \text{fm}$$



$$\hat{q} = \frac{\mu^2}{\lambda_g} = 10 \text{ GeV}^2 / \text{fm}$$

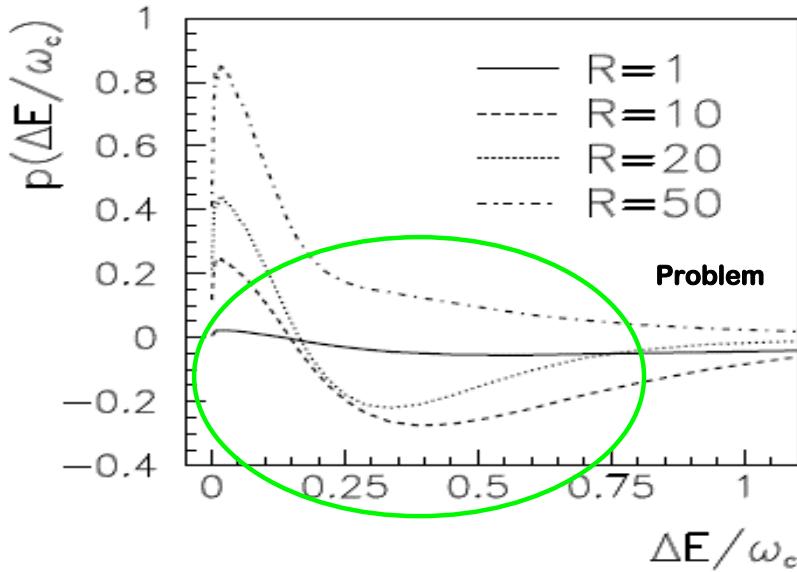
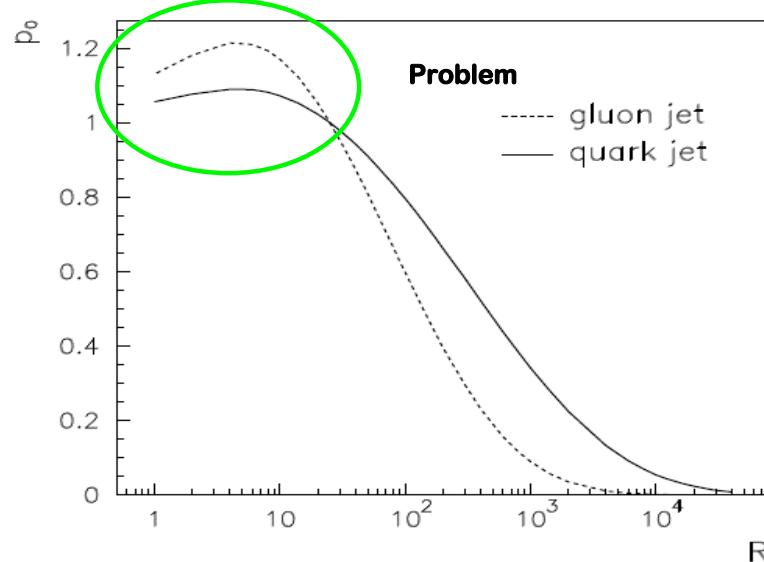
LHC: from $T = 1 \text{ GeV}$



Ivan Vitev, LANL

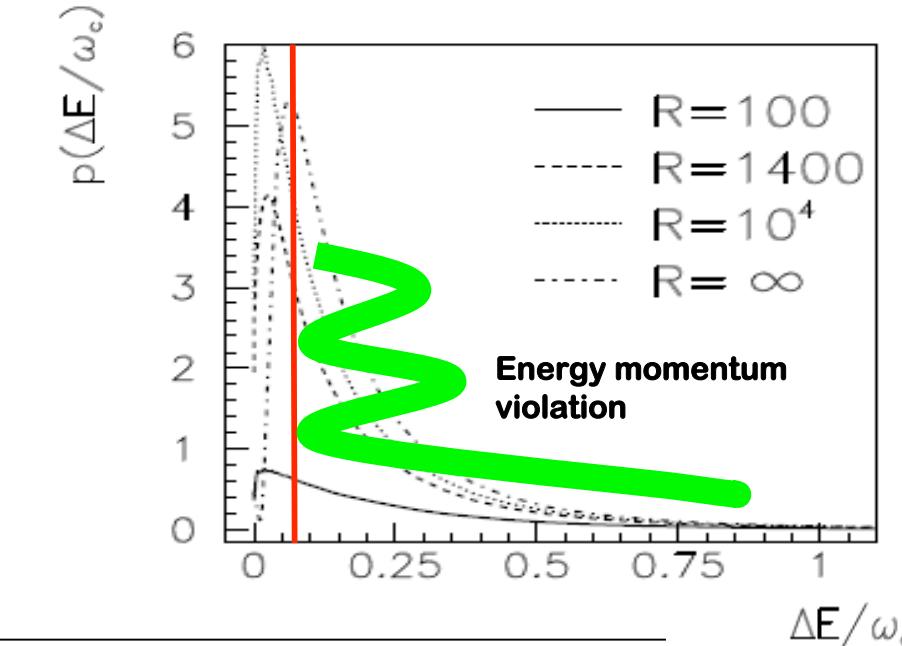


Differences Between Models



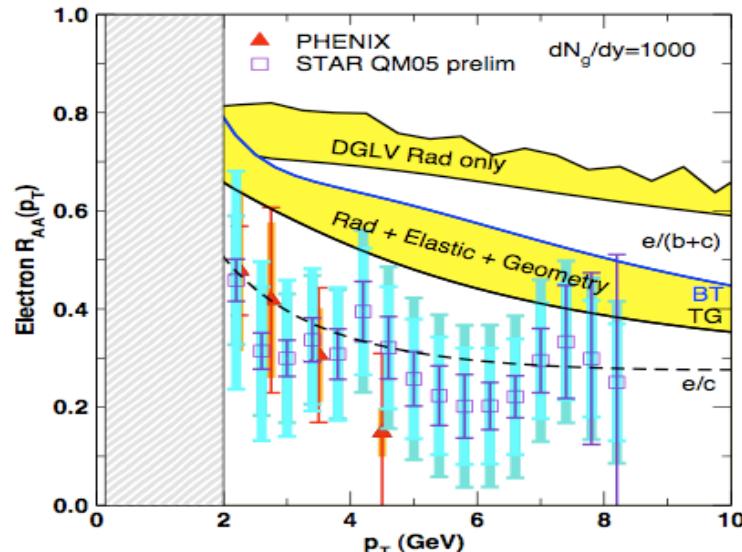
$\omega_c (L=5 \text{ fm})$	R
$\hat{q}_{200 \text{ GeV}} \approx 14 \text{ GeV}^2/\text{fm}$	350 GeV ~ 10000
$\hat{q}_{5500 \text{ GeV}} \approx 100 \text{ GeV}^2/\text{fm}$	2650 GeV ~ 100000
Typical gluon energy $\omega_c = \hat{q}L^2 / 2$ $R = \omega_c L$	

- Note that the region of P_T at RHIC is 10-20 GeV and at the LHC 100-200 GeV



Non-Photonic Electron / Heavy Flavor Quenching

Proceed to A+A collisions

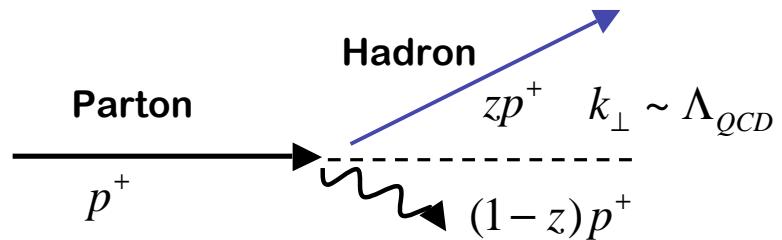


S. Wicks et al., nucl-th/0512076

- Single electron measurements (presumably from heavy quarks) may be problematic for mainstream theory
- Is it accidental or is it symptomatic?

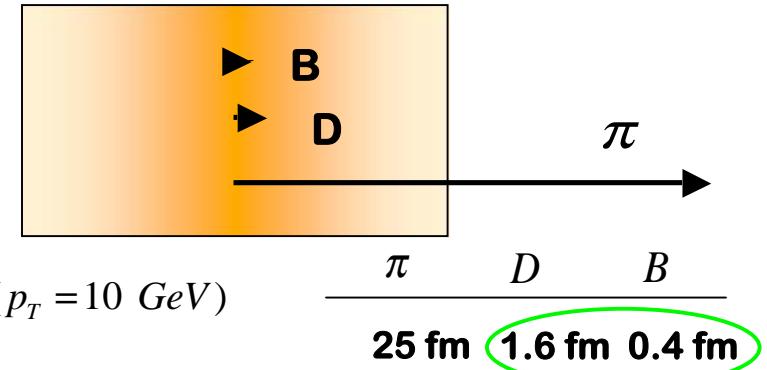


- Hadron formation time



$$\Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2 \text{ GeV.fm}) 2z(1-z)p^+}{k_{\perp}^2 + (1-z)m_h^2 - z(1-z)M_q^2}$$

QGP extent $\sim 5 \text{ fm}$



- New approach needed

Scope of PQCD Heavy Flavor Effort

Publications

- *Ivan Vitev, Terry. Goldman, Mikkel Johnson, Jian-Wei Qiu, NUCLEAR EFFECTS ON OPEN CHARM PRODUCTION IN P+A REACTIONS. Phys. Rev. D 74: 054010 (2006)*
- Azfar Adil, *Ivan Vitev, COLLISIONAL DISSOCIATION OF HEAVY MESONS IN DENSE QCD MATTER. Phys.Lett.B: in press (2007)*
- *Ivan Vitev, NON-ABELIAN ENERGY LOSS IN COLD NUCLEAR MATTER. Submitted to Phys.Rev.C (2007)*
- *Hendrik van Hees, Ivan Vitev, Ralf Rapp, HEAVY FLAVOR MODIFICATION IN A COMBINED TRANSPORT+QUENCHING APPROACH. In preparation*

Collaborators

- T. Goldman, M. Johnson, T-16 and P-25 Los Alamos National Laboratory
- A. Adil, Columbia U., J.-W. Qiu, Iowa State U., R. Rapp, H. van. Hees, Texas A&M U.
- LDRD DR project team, T-8 and P-25 Los Alamos National Laboratory

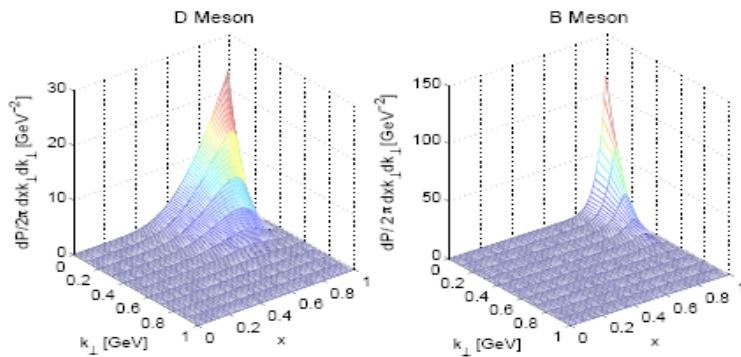
Presentations

- *Ivan Vitev, Strangeness in Quark Matter, UCLA, Los Angeles, CA, March 2006*
- *Ivan Vitev, Quark Matter 2006, Shanghai, China, November 2006*
- *Ivan Vitev, Heavy Flavor Workshop, Beijing, China, November 2006*
- *Ivan Vitev, T-16 Seminar, Los Alamos, March 2007 ...*

Heavy Meson Dissociation Rates

- Light cone wavefunctions for heavy mesons

$$|\psi(\Delta k_\perp, x)|^2 \sim \text{Exp} \left[-\frac{\Delta k_\perp^2 + 4m_Q^2(1-x) + 4m_q^2(x)}{4\Lambda^2 x(1-x)} \right]$$



$$P_{\text{surv.}} \left(\frac{\mu^2}{\lambda} L \xi \right) = \left| \int dx d^2 \Delta k_\perp \psi_f^*(x, \Delta k_\perp) \psi_i(x, \Delta k_\perp) \right|^2$$

Function of the cumulative transverse momentum transfer

- Coupled rate equations

$$\begin{aligned} \partial_t f^Q(p_T, t) &= -\frac{1}{\langle \tau_{\text{form}}(p_T, t) \rangle} f^Q(p_T, t) \\ &\quad + \frac{1}{\langle \tau_{\text{diss}}(p_T / \bar{x}, t) \rangle} \int_0^1 dx \frac{1}{x^2} \phi_{Q/H}(x) f^H(p_T / x, t) \\ \partial_t f^H(p_T, t) &= -\frac{1}{\langle \tau_{\text{diss}}(p_T, t) \rangle} f^H(p_T, t) \\ &\quad + \frac{1}{\langle \tau_{\text{form}}(p_T / \bar{z}, t) \rangle} \int_0^1 dz \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T / z, t) \end{aligned}$$

... which we solve with the **initial conditions**

$$\begin{aligned} f^Q(p_T, t) &= \frac{d\sigma^Q(p_T, t)}{dy d^2 p_T}, \quad f^H(p_T, t) = \frac{d\sigma^H(p_T, t)}{dy d^2 p_T} \\ f^Q(p_T, t=0) &= \frac{d\sigma_{PQCD}^Q}{dy d^2 p_T}, \quad f^H(p_T, t=0) \equiv 0 \end{aligned}$$

... to find the **asymptotic solutions**

$$t \gg \max(L_{QGP}, \tau_{\text{form}})$$

Quenching of Non-Photonic Electrons

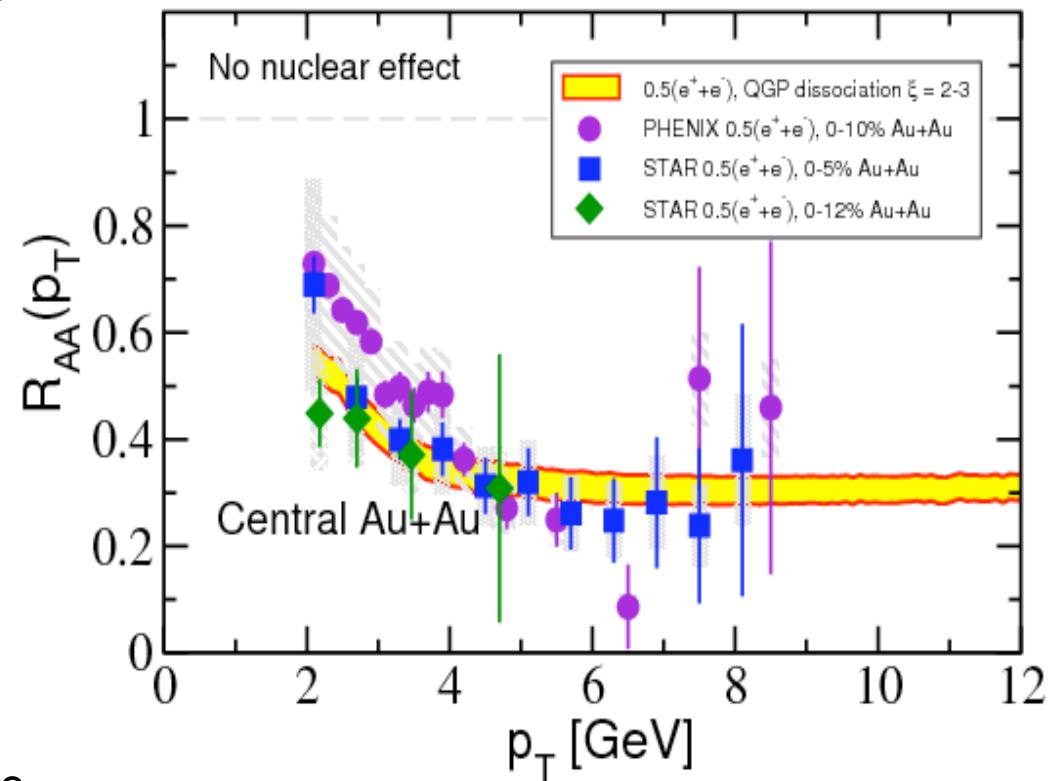
- PYTHIA used to decay **all** B- and D-mesons / baryons into ($e^+ + e^-$)

$$\sum_{i=1}^n f_i(B/b; D/c) = 1$$

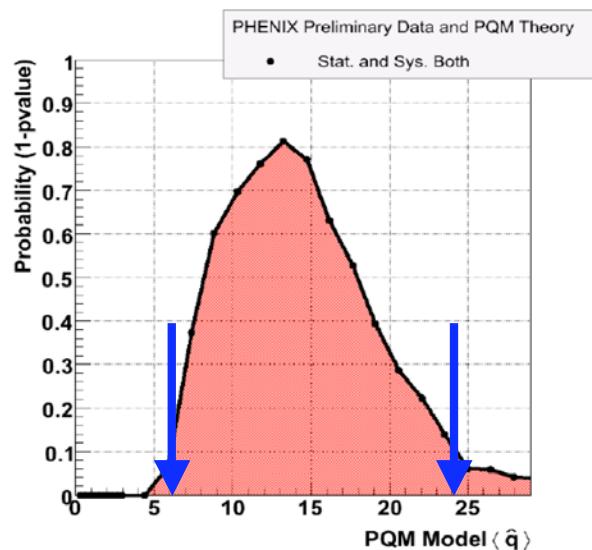
- Suppression $R_{AA}(p_T) \sim 0.25$ is large

$$R_{AA}^{e^\pm}(p_T) = \frac{dN_{AA}^{e^\pm} / dy d^2 p_T}{\langle N_{coll} \rangle d\sigma_{pp}^{e^\pm} / dy d^2 p_T}$$

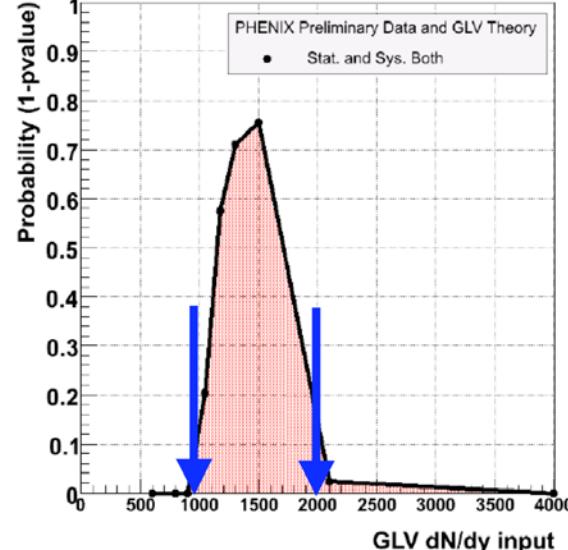
- Similar to light π^0 , however, different physics mechanism
- B-mesons are included. They give a major contribution to ($e^+ + e^-$)



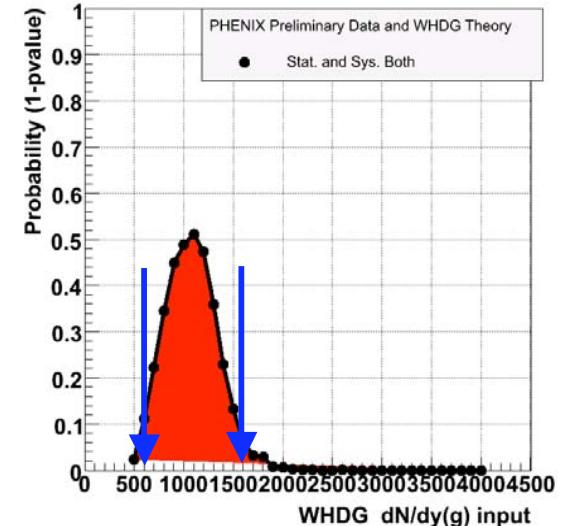
Comparing $\pi^0 R_{AA}$ to theory



$6 \leq \langle \hat{q} \rangle \leq 24 \text{ GeV}^2/\text{fm}$
(Probability $> 10\%$)



$1000 \leq \frac{dN_g}{dy} \leq 2000$
(Probability $> 10\%$)



$600 \leq \frac{dN_g}{dy} \leq 1600$
(Probability $> 10\%$)

Add stat and uncorr point-to-point syst err in quadrature – χ^2 minimization fit to obtain the probability of a given parameter

Then offset the data points by ± 1 RMS of the correlated syst errors and do the same

Sum up 1 & 2 to obtain the curves above

Little sensitivity to model parameters

D- and B-meson Suppression at RHIC and LHC

- Suppression $R_{AA}(p_T) \sim 0.25$ is large
- Similar to light π^0 , however, different physics mechanism
- B-mesons as suppressed as D-mesons at $p_T \sim 10$ GeV (unique feature)
- A chance to really determine the physics of heavy flavor suppression

Velocity factor $\beta = p / E$
important at small/intermediate p_T

